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Integrated Economy/Energy/Environment Models

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Abstract

The paper presents a review of alternative methodologies in the field of economy, energy and environment (E^3) modelling with particular emphasis on the computable general equilibrium approaches, and the European Commission's newly developed models

The GEM-E3 model (general equilibrium model for economy, energy, environment), developed for the European Commission (DG-XII/F1) by a consortium involving NTUA, CORE, KUL, University of Mannheim and CEA, follows the computable general equilibrium methodology, as based on the Arrow-Debreu theory. The model considers multiple production sectors, multiple economic agents and multiple countries (European Union) which interact through perfectly competitive markets for goods, labour and capital. The model's output includes full Input-Output tables, National Accounts, Employment, Trade, Monetary and other macro-economic variables for all European Union countries. GEM-E3 considers explicitly the energy sectors, abatement costs, atmospheric pollutants (including CO_2) and related policy instruments (e.g. taxes, pollution permits etc.). The model's design seeks to provide a general purpose tool for macro-economic analysis and the study of economic implications of energy and environment strategies. The model operates dynamically along a path of general equilibrium solutions.

The energy model PRIMES (price induced model of the energy system), developed for the European Commission (DG-XII/F1) by a consortium involving NTUA, CORE, KUL, IFP, COHERENCE and ETSU, also follows a market-oriented approach. PRIMES is a detailed energy system model with an explicit representation of technologies. It is modular, consisting of energy demand and supply sub-models. Each sub-model reflects the energy-related economic decisions of an agent (demander and/or supplier). The sub-models interact within a set of energy product markets that may be governed by alternative market-clearing regimes. These interactions determine energy prices and ensure equilibrium between energy demand and supply. PRIMES follows a very detailed nomenclature for energy products and technologies and covers the European Union countries.

1. Overview of Energy-Economy-Environment Modelling Approaches

The objective of Energy - Economy - Environment (E3) modelling is to study the interactions between macro-economic, energy and environment systems, linked together through a closed loop. The discipline finds its origin in the 70s through economy-energy modelling and the seminal work of several modellers, such as D. Jorgenson (see [1] and [2]) and A. Manne (see [3]). A natural extension is the incorporation of environmental mechanisms, considering implications for the biosphere, abatement costs and externalities. Integrated models include specific system models for the three parts of E3 and formulate effects and feedback. Integration does not necessarily mean uniformity in the modelling approaches for the three parts. The development of E3 integrated models is still challenging the research community, because of their methodological, computer and mathematical complexity.

Methodological paradigms are currently dominated by the economic general equilibrium theory. Through such an approach, projections and counterfactual model simulations can be interpreted for normative policy analysis (contrary to descriptive approaches).

1.1. New Challenges for E3 Modelling

During the last five years, the emergence of the global climate change threat from energy-related emissions of carbon dioxide (CO_2), has triggered highly qualified research on modelling the interactions between the energy, economic and environmental systems.

Earlier work in this field was concerned with modelling energy-economy interactions in the context of energy supply shortages or high prices. Between 1974 and 1983, this led to the development of an important range of modelling techniques and methodologies, such as the general equilibrium modelling of D. Jorgenson, the system optimisation models of A. Manne and others (for a tutorial on different techniques used in energy systems analysis, see [4]).

The new issues related to CO_2 emission reduction are more challenging, since they imply:

a) more complexity because global energy, economy and environmental systems are affected,

b) more uncertainty because it is necessary to deal with a longer term horizon and technology change,

c) more difficulty because we need to represent decentralised decisions in a market-oriented paradigm (in contrast to government planning) since current problems occur in the context of accelerated market liberalisation world-wide.

To satisfy these three requirements in a single empirical model, still remains a challenging mathematical and computing problem. All the available empirical models in the field focus on more on one or two of the above requirements, while substantially neglecting the third one, in order to reduce the computational burden. For example, detailed technological models satisfy the second requirement, but often neglect market-related decentralised behaviour of agents and cover only the energy-environment systems. Macro-economy oriented models may well represent market-orientation, through the economic equilibrium paradigm, but often neglect the technological change aspects and the energy system details. Finally, growth models which cover the long term evolution of the economy and deal with technological change, often neglect the individual behaviour of agents in a market context.

This situation limits the insight we can have on new issues. One then needs to combine approaches and models, reconcile results and work on a synthesis of partial conclusions.

1.2. Limitations of Older Approaches

The earlier detailed technological models are usually characterised as bottom-up approaches. Usually they are based on a mathematical programming (optimisation) problem which covers the energy system or even the energy-economy-environment system. In the former case, for example EFOM (see [5]), MARKAL (see [6]), BESOM (see [7]), they are mainly used for energy technology characterisation and forecasting within the context of a perfect market. In the latter case, for example

ETA-MACRO (see [3]), Goulder's model (see [8]), Global 2100 (see [9]), ERM (see [10]), DICE (see [11]), the models are usually driven by economic growth theory and attempt to study the implications of technology change and CO_2 mitigation options on long term growth.

Both the above types of models are often criticised for the lack of explicit representations of markets, related policy instruments and individual behaviour of agents. The efficiency gap problem illustrates this point. The bottom-up approaches identify the existence of an energy efficiency potential that may be achieved without extra cost to the system (a sort of free resource). However, in reality there is no evidence of the existence of such an efficiency potential. This is called the "efficiency gap" (see [12]). Micro-economic analyses suggest that the gap can be explained by specific conditions that prevail in the markets (distortions, barriers, etc.) and by the different behaviour of economic agents (for instance, small consumers may use high subjective discount rates).

1.3. The Emergence of Market-Oriented Approaches

The above reasons, together with the need to represent the growing process of market liberalisation, motivated analysts to adopt market-oriented modelling approaches that involve explicitly market regimes and model separately the behaviour of economic agents. Such models can incorporate detailed representations of policy instruments and structural options that can alleviate the efficiency gap problem. They are often called "new generation models" and currently prevail in policy analysis studies.

Examples of such energy-environment system models, are IFFS (see [13]), GEMS (see [14]), GEMINI (see [15]), ENPEP (see [16]), NEMS (see [17]) (all from the USA) and PRIMES (see [18]) for European Union. These models are often characterised as partial equilibrium models because they cover only the energy system and not the rest of the economy. They are also known as generalised equilibrium models because they can describe different behavioural circumstances for the economic agents by using different mathematical formulations for the sub-models, and different market clearing regimes, by using different algorithms for global convergence (equilibrium).

Similar aims led analysts to propose general equilibrium models that consider the whole spectrum of economy, energy and environment interactions based on market-oriented formulations. This trend joined, as expected, the independent efforts of economists in the field of "pure" macro-economic models. There one can find the various macro-economic paradigms that dominated their modelling activities, mainly the neokeynesian and the neo-classical approaches (see [19]). The former accepts disequilibrium conditions in the markets and can provide projections for the short/medium term, for example HERMES (see [20]). The latter, which dominates current development work, formulates price-driven market equilibrium regimes and allows for a normative characterisation of policies and structural change, for example the computable general equilibrium models, such as those developed within World bank activities (see [21]). The nature of policy issues concerned with economy-energy-environment interactions requires a computable equilibrium approach for several reasons: structural change is involved in market regimes and technology; the market competition paradigm prevails in current policy analysis, as mentioned previously; the evaluation of policy measures must be undertaken by considering comparable projections (since all projections attain general equilibrium).

1.4. Modern E3 Models

The attractiveness of computable general equilibrium models inspired analysts to extend the models to include more details (or new sub-models) covering the interactions with the energy sector and environment. Through these extensions, the general equilibrium is achieved simultaneous for all three systems. This is achieved as follows:

- all markets clear simultaneously, for example markets for goods, labour, energy markets, pollution permits markets etc.;
- the optimisation behaviour of suppliers incorporates the costs and constraints from environmental policies (abatement, policy limits, taxes);
- the optimisation behaviour of consumers considers the environmental dimension involving costs and damages, which generally influence the consumer's utility;

- the energy sector contains engineering detail, for example in electricity supply;
- the policy instruments considered for energy and environment policies are explicitly included in the model, so as to support policy analysis.

The pioneering work along these lines was provided by D. Jorgenson (DGEM model, see [22]), while GREEN (OECD, see [23]), GEM-E3 (European Union, see [24]) and other models were built more recently.

1.5. Integrated Assessment Approaches

For the analysis of global climate change issues, particularly for the long term, the method of integrating the environmental system representation in the economic model is of importance. The feedback effects from climate change to the economy are particularly difficult to evaluate, because of the complexity of environmental changes and the global nature of the interactions. This triggered the development of global assessment models that attempt to establish detailed links from the emissions through the economic valuation of damages, taking into account global climate change. In addition to the economic equilibrium model, these approaches integrate models for geophysical simulation including geographic specificity, for example IMAGE (see [25]), MERGE (see [26]), DICE (see [11]).

From an economic point of view, however, two problems arise regarding the integration of environment effects with the economy:

- first, the formulation of utility (or welfare) changes induced by environment degradation, which is a challenging problem;
- second the valuation of damages, in other words the quantification of externalities.

For the latter, several accounting procedures have been proposed that usually map physical damages to health, living conditions and society, for example the EXTERNE project of the European Commission (see [27]).

1.6. Categorisation According to Model Use

The way that energy-economy-environment models are used in practice has important implications for their formulation. We consider a general distinction between:

- general purpose models, developed not only for climate change analysis, but also to analyse other policies
- models specifically developed for the climate change issue.

The latter are generally more simplistic than the former ones, particularly with respect to policy instruments, their representation of technology assumptions and the economy. The climate change models need to cover the global character of climate change mechanisms, together with economic growth and technology evolution over very long time-scales.

The general purpose models are more detailed and realistic, cover a shorter time horizon, but are not able to fully represent the longer term re-structuring and feedback effects relevant to climate change.

An illustration is the treatment of the backstop technology. This is considered to be a non-identified technology, possibly carbon-free, that has to replace current technologies in the very long term so as to achieve global objectives. All long-term models specific to climate change issues use the concept of a backstop technology (or fuel) and most of the conclusions are mainly attributed to this technology and depend heavily on its numerical characteristics (this tends to be independent of the approach of the model, for example, Global 2100, Green). On the contrary, the concept of a backstop technology does not exist in general purpose models, since it is not identifiable from current knowledge. These models do not, therefore, exploit the likely full potential for CO_2 mitigation, but on the other hand they do not rely on such uncertain information.

1.7. The European Commission Experience

The work supported by the European Commission is also characterised by similar trends in the modelling field, as described above.

The older models of the European Commission were built for specific purposes, different to those currently requiring integrated assessment approaches. The EFOM model was a detailed technological model for the energy system and followed a general system optimisation methodology. To study acid rain policies, the model was extended with pollution abatement modules for all energy activities and increased technological detail. As the CO_2 mitigation issue became politically important, the EFOM model (CRASH programme of DG-XII, see [28]) provided analysis of technological change needed to support CO2 objectives. This is one of the examples of studies that estimated an energy efficiency gap, as mentioned before. In parallel to EFOM, and mainly to meet the needs of macro-economic policy analysis, the HERMES model was developed, following a rather traditional neokeynesian methodology. It was used first for internal market studies, and then it was used to study the macro-economic consequences of carbon taxes and related policy measures.

The MIDAS energy model (see [29]) was the first European Commission model that separated the representation of behaviour of agents (energy demanders and suppliers) and formulated explicitly cost-price setting mechanisms. However, there was not explicit treatment of competitive market regimes, apart from monopolistic competition ones. MIDAS was highly detailed in supply side but econometric in demand side. For this reason, MIDAS was used mainly for smooth projections and scenario construction. It was the main model used for analysis of the implications of carbon tax policies.

Following the general trend, the European Commission re-oriented their modelling work towards the market competition paradigm, both for energy (PRIMES) and the economy (GEM-E3). PRIMES follows the generalised equilibrium methodology to model the energy system and GEM-E3 adopts the computable general equilibrium approach with integrated feedback mechanisms between all three systems, namely economy, energy and environment. Both models were conceived specifically for the study of climate change strategies but also for other purposes. They do not consider the very long term, nor integrated assessment as required for global analysis. However, they include economic valuation of damages. Both models fully support the need to study technology and economic policy in the context of growing competition in the markets.

Over the next two years, the European Commission is launching a new integrated study dealing with the analysis of climate strategy and technology policy within competitive markets. This study will use the market-oriented models, mentioned above, to set up a normative strategy for technological development and adequate accompanying measures such that new growth potential is created which is sustainable with respect to climate change constraints. The main issue is to set up such a policy within the context of liberalised markets, so as to ensure consistency with individual behaviour and market regimes. Policy measures to be considered are characterised according to the general concept of internalisation of externalities. The latter will be appraised following the results of the EXTERNE project (DG-XII).

2. The GEM-E3 Model

2.1. General presentation of the model

The GEM-E3 model, is an operational, empirical model, that follows the computable general equilibrium methodology. The model aims at representing the interactions between the economy, the energy system and the environment. It clears the market at both the country-specific (European Union member-states) and the Europe-wide levels.

The general structure of the macro-economic core of GEM-E3 is illustrated in figure 1.

The model has the following features:

(i) It represents multiple sectors and multiple countries.

(ii) It clears simultaneously the markets of commodities and primary factors (labour, capital).

(iii) It represents energy forms and environmental policy instruments.

(iv) The equilibrium prices for the above markets are explicitly computed, so that the model is able to support policy analysis of taxation and alternative market clearing regimes.

(v) The formulation of behavioural equations and the closure rule are such that the model simulations cover both the medium and the long term.

(vi) Capital stock is fixed within the year, but accumulates over time through endogenously driven investment.

(vii) A set of other mechanisms, such as stock-flow consistency and backward looking anticipation complete the dynamics of GEM-E3.

The model considers simultaneously the European Union countries linked together and in the same time with the rest of the world. The model is constructed as a single system of equations that incorporate simultaneously the equilibrium markets of all European countries. Endogenous foreign trade links the countries forming a closed loop. This is formulated in a way to ensure, in all cases: equality between imports by one country and the corresponding exports of another country (in volume and value), a condition that corresponds to a trade matrix and zero trade deficit (in value) at the global level.

The model provides three axes for use in policy analysis: (a) sustainable economic growth (with respect to the environment); (b) internal European market (for economy and energy); (c) European perspectives within an evolving international context (for both the economy and energy).

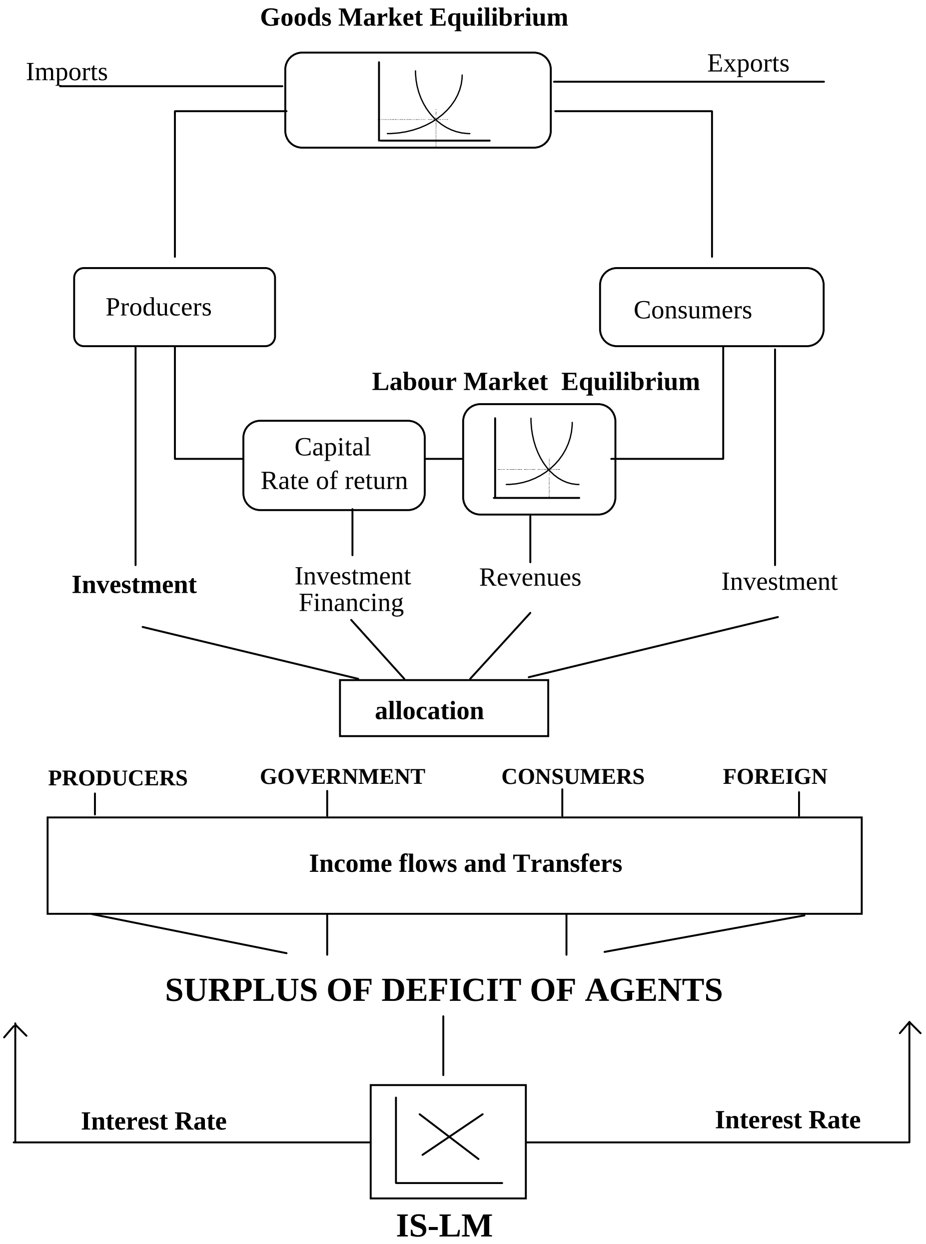


Figure 1. The general scheme of the model.

A major benefit of using GEM-E3 in policy analysis support is the consistent evaluation of distributional effects, across countries, economic sectors and (in the next future) social groups. The burden sharing aspects of environmental protection is thus fully analysed, while ensuring that the European economy remains at general equilibrium conditions.

2.2. Domestic Production

Production functions exhibit a nested separability scheme, involving capital (K), labour (L), energy (E) and materials (M). Energy is further divided into electricity (El) and other fuels.

Firstly, production splits into two aggregates, one consisting of capital stock and electricity and the

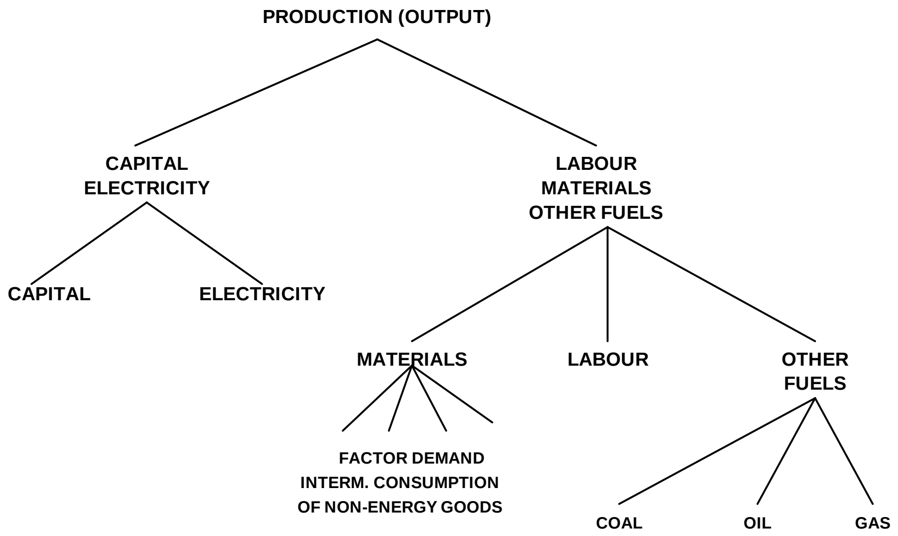


Figure 2. Domestic production scheme

other of the aggregate of labour, materials and other fuels. At the second level, the two ensuing production functions are further divided in their component parts. The constant elasticity of substitution (CES) specification is used throughout.

Figure 2 illustrates the nesting of the production function.

The model formulates domestic supply of goods through the above production functions and assumes a constant return of scale and exogenous rates of technical progress. At the equilibrium point, the derived demand for production factors (labour, energy, material, capital services) are such that all sectors maximise profits at zero-profit level. Capital is considered fixed in the short term, therefore the supply function is positively sloped exhibiting diminishing returns. Capital is accumulated dynamically through investment.

2.3. Households final consumption

Households' decisions concern, first, income and leisure so as to maximise an inter-temporal utility function under an inter-temporal budget constraint. Then income is further divided in consumption, investment in physical assets (dwellings) and investment in monetary assets (savings). Finally total consumption is divided into demand categories through a Linear Expenditure System which covers all durable and non durable goods. The demand for consumption categories is then transformed into a demand for products by means of a transition matrix with fixed technical coefficients. Figure 3 presents the general separability scheme of the consumption of households.

Households consume a range of durable goods (cars, heating systems, electric appliances and investment in dwellings) and non-durable goods which are grouped in consumption categories (food, culture etc.). Durable goods demand the consumption of some non durable goods (e.g. cars consume gasoline). Therefore non-durable goods are linked with the stock of the durables. These goods are electricity, oil, motor fuels and other fuels. For all durables it is assumed that they use a fixed proportion of energy sources.

Finally labour supply is also decided within this module, as derived from preferences for leisure.

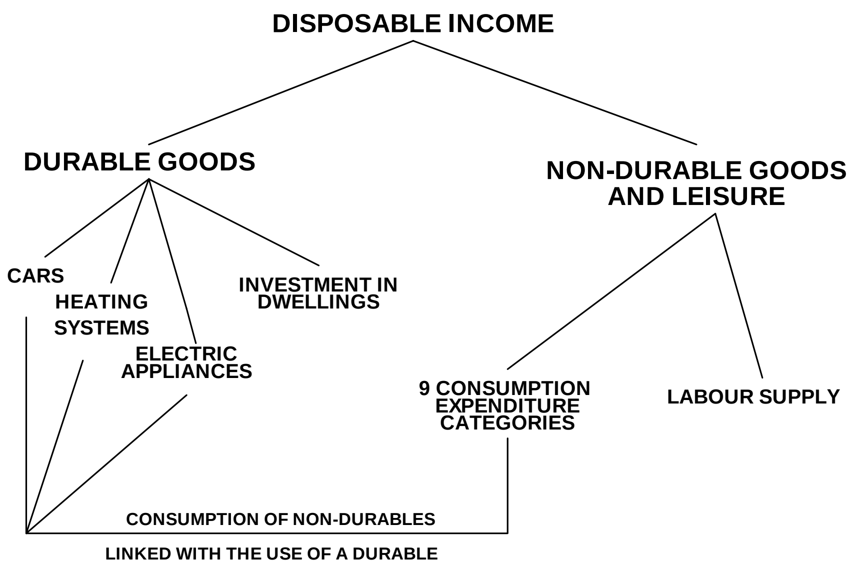


Figure 3. Households final consumption

2.4. Foreign trade

The model is not covering the whole planet and thus the behaviour of the rest of the world (ROW) is left exogenous. However, the European Union member-states are endogenously linked through trade of goods and services.

The exogenous imports demanded by the ROW are flexibly satisfied by exports originating from the European Union (EU) countries. The latter however, consider the profitability of exporting to the ROW, exporting to the EU or addressing the goods to their domestic markets. Through these profitability considerations, the EU countries set their export prices. A modified export supply function represents these mechanisms, following a constant elasticity of transformation formulation (CET).

Imports demanded by the EU countries from the ROW are supplied flexibly by the latter. However, the EU countries consider the optimal allocation of their total imports across the countries of origin, according to the relative import prices. The EU countries buy imports at the prices set by the

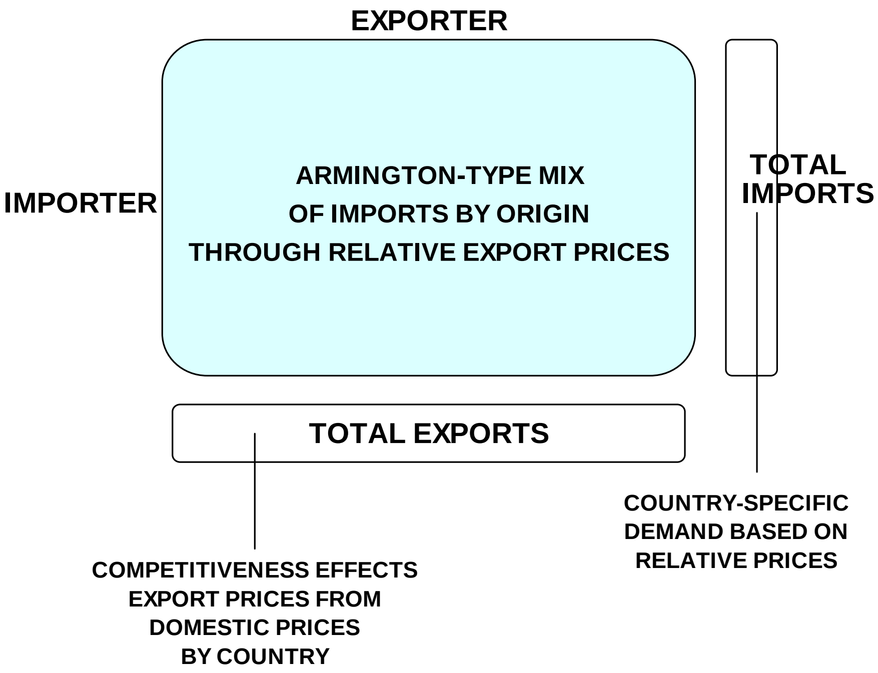


Figure 4. Trade matrix for EU and the rest of the world

supplying countries following their export supply behaviour. Of course, the supplying countries may gain or loose market shares according to their price setting. When importing, the EU countries compute an index of mean import price according to their optimal allocation by country of origin. This mean import price is then compared to the domestic prices in order to allocate demand between imports and domestic production. A nested two-level Armington function represents this mechanism.

A trade flow from one country to another matches, by construction, the reverse flow. The model ensures this symmetry in volume, value and deflator. It is obvious, then, that the model guarantees (in any scenario run) all balance conditions applied to the world trade matrix, as well as the Walras law at the global level. Of course, all these are validated on the same currency basis, namely the ECU.

Figure 4 illustrates the trade matrix as described above.

2.5. Income accounts

The real sector of the model is grouped within the framework of a Social Accounting Matrix - SAM (figure 5), which ensures consistency and equilibrium flows from production to the agents and back

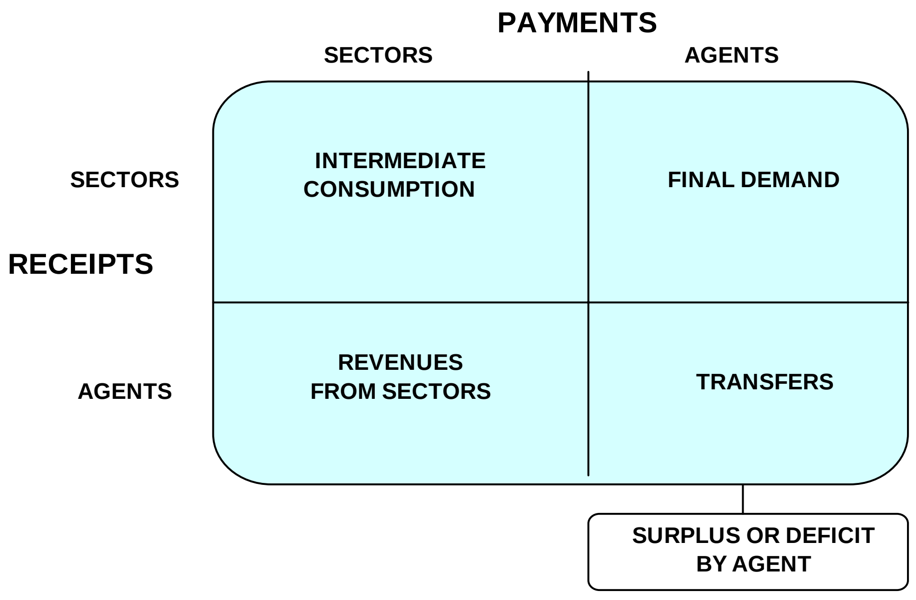


Figure 5. Social Accounting Matrix (SAM)

to consumption. The construction of the SAM is the starting point for building the model. The definition of the set of prices, ensures the consistency of the SAM, (in current currency). This is reflected by the above condition, which states that the algebraic sum of net savings over the set of agents is, by construction, equal to zero.

The economic agents are households, firms, government and the Rest of the World. The sources of income for consumers and producers are labour and capital rewarding. The sources of income for government are transfers and taxes. The agents use income for consumption or investment. Finally the surplus or deficit by an agent equals their net savings minus investment.

2.6. Equilibrium of the real part

The equilibrium of the real part is achieved simultaneously in the goods market and in the labour market. Figure 6 presents the equilibrium of the real part for both markets.

In the goods market a distinction is made between tradable and non tradable goods. For the tradable goods the equilibrium condition refers to the equality between the supply of the composite good, related to the Armington equation, and the domestic demand for the composite good. This equilibrium combined with the sales identity, guarantee that total resource and total use in value for each good are identical. For the non tradable, there is no Armington assumption and so the good is homogeneous. The equilibrium condition serves then to determine domestic production.

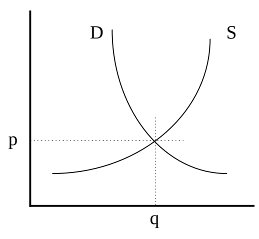


Figure 6. Equilibrium of the real part

For the labour market full employment is postulated. Here the equilibrium condition serves to compute the wage rate, as the remaining equilibrium price.

The closure rule (as residual) could be the public budget or the balance of payments. It is also possible to implement other closure rules (for example, fixed balance of payments and exchange rate endogenous).

Instead, the current model version uses an IS-LM type of closure. The model closure is defined by representing the way agents finance their deficit or allocate their surplus. The closure considers explicitly the banking sector, the allocation of private assets, the financing of public budget and the balance of payments. It determines interest rates of equilibrium in the financial/monetary sector. Through this closure, all prices are endogenously evaluated and there is no need for assuming an arbitrary “numeraire”. The interest rates of equilibrium exert further feedback effects to the real sector of the model, affecting investment decisions of agents and influencing the dynamic path.

The formulation is inspired from the methodology of Bourguignon, , de Melo, Branson (see [30]) and Capros et al. (see [31]).

2.7. The Financial/Monetary sector

The financial behaviour of economic agents is based on a portfolio model which is derived by maximising expected utility. The model allocates financial wealth among various assets. The allocation is made using logistic curves to ensure better simulation behaviour (for a general description see [32]). Such an approach avoids reduced-form models of financial mechanisms and uses relative interest rates as explanatory variables. Depending on whether liberalised capital markets are represented in the model, these interest rates can be derived from the equilibrium of financial supply and demand flows.

Regarding its accounting structure, the model is based on a matrix of flows of funds (Table 1), involving four financial agents, namely the private, government, banks [1] and foreign sectors.

[1] The banking system, as defined in this model comprises, beside the central bank, all commercial banks and specialised credit institutions.

	PRIVATE	BANKS	GOVERNMENT	FOREIGN
ASSETS	placement of assets	supply of credits and loans		transfer and financing of foreign debt
LIABILITIES	credits and loans	deposits	financing of deficit	

Table 1. The matrix of flow-of-funds

In the model the foreign and public sectors are represented only with respect to the financing of their surpluses, while the banking and private sectors are represented following an "assets-liabilities balance" approach. However, the model fully guarantees stock-flow consistency for all transactions.

On the assets side of the private sector, total wealth is evaluated, dynamically, by private net savings, a variable coming from the real part of the model.

The allocation of total wealth of the private sector is described as "risk averse investment behaviour". Private agents are assumed to maximise the utility of the return from a portfolio. In this respect future returns are uncertain and the risk aversion is formalised as diminishing marginal utility. The placement of assets is a function of returns and interest rate. The optimum portfolio composition, involves cash, time deposits, saving deposits, government bonds, bank bonds and treasury bills. The allocation mainly depends on the relative rates of return (assimilated to interest rates) from the above assets.

The real sector defines the demand for credit and loans. The supply of credit and loans is limited by the need to finance government budget deficit.

Domestic borrowing of government is divided into two parts: the treasury bills and the government bonds. Both can be acquired by the private sector and by commercial banks. In the private sector, investment in these two assets emanates from portfolio allocation.

2.8. Representation of the environment

The model evaluates the energy-related emissions of CO_2, NO_X and SO_2 as a function of energy consumption and the abatement level per branch and per sector. The abatement level is endogenous and is linked to production function through abatement costs which will increase the cost price of using pollution intensive inputs.

The emissions are used to calculate pollutant concentrations or deposition, taking into account the transportation (between countries) and transformation mechanism of the pollutants.

In a final step, the damage generated by the concentration/deposition of pollutants is computed in physical units and valued in monetary units through a valuation function.

The model covers a wide spectrum of environmental policy instruments, including taxes, subsidies and pollution permit markets (regional and European).

2.9. Nomenclature/Dimensions of the model

The model covers:

- 11 countries (all EU countries except Luxembourg)
- 11 products and sectors: 4 energy branches (electricity, oil, gas and coal); 3 industrial branches (energy intensive, equipment goods and consumer goods industries); transport, market services and public services.
- 4 economic agents: households; firms; government; rest of the world.
- 8 government revenue categories: direct, indirect taxes and VAT; subsidies, import duties and foreign sector transfers; social security and government enterprises.

- 13 consumption expenditure categories: 9 consumption categories (food, culture, health, electricity, gas, motor fuels, other fuels, transport, house); 3 durables (cars, heating systems, electrical appliances); investment in dwellings.
- 2 primary production factors: labour; capital.
- 3 pollutants: CO_2, SO_2, NO_X.
- Annual time path: The model is solved annually and follows a time-forward path.
- Software: The model is solved following a combined Gauss-Seidel and Newton Successive Over-Relaxation method by using the SOLVER/NTUA software operating in MS-Windows.

3. The PRIMES Model

3.1. General Presentation of the Model

The ***PRIMES*** model focuses on major areas energy policy analysis:

- the prospects and economics of new energy supply and demand technologies;
- the energy-environment interactions and the evaluation of related policy instruments, including taxation, regulations, pollution permits, abatement technologies, energy savings and improved energy conversion technologies;
- the internal market for energy, including the consequences of third party contracting in the electricity and gas, and the implications of opening up competition in the energy sector;
- the implications of the evolving international context for energy supply to the Community, including the "energy charter" requirements.

3.2. Model Characteristics

PRIMES is a partial equilibrium model for the European energy system and markets, including full coverage of their implications on the environment. The model:

- explicitly computes the energy prices of equilibrium (i.e. a computable equilibrium model) and permits policy analysis of market oriented taxes, regulations and pollution permits;
- has a flexible modular structure, allowing both for the gradual incorporation of markets and for individual and customised mathematical formulation of the demand and/or supply behaviour of agents (i.e. a generalised equilibrium model);

- covers in full detail, both the country-specific energy systems and the overall energy market clearing at the European Community level (i.e. a combined national and multinational equilibrium model);
- combines an engineering-oriented representation of energy supply, savings, abatement, costing and technologies with analytical economic functions for energy demand and fuel substitution; disaggregation is based on the Eurostat scheme of analytical energy balance sheets, for demand, and the EFOM data base for supply; multinational markets and exchanges are included for the electricity grid, the natural gas and the refinery sectors.

3.3. Main Model Mechanism

PRIMES is oriented towards the price-driven equilibrium paradigm. The model is designed to support energy policy analysis and has the following characteristics:

- it considers explicitly and computes the formation of energy prices, enabling the study of price-related and market-related policy instruments; a main policy example is the carbon tax and carbon permits instruments;
- it represents market clearing mechanisms and related behaviour as the main explanatory force, enabling realistic forecasts to be made given the increasing trend towards liberalisation of markets;
- it recognises the individual character of agents' behaviour (for example, different discount rates), and abolishes the central planning paradigm, by modularising the model and decentralising optimisation behaviour;
- it maintains a sufficient degree of disaggregation of sectors and technologies, and places sufficient emphasis on the interdependencies between the country-wide models, to reflect internal market perspectives; the representation of market-related mechanisms comply with this latter objective

and include the representation of market-clearing at the European-wide level (for example in the gas sector).

A fundamental assumption in ***PRIMES***, is that producers and consumers both respond to changes in price. The factors determining the demand for and the supply of each fuel are analysed and represented, so they form the demand and/or supply behaviour of the agents. Through an iterative process, the model determines the economic equilibrium for each fuel market. Price-driven equilibrium is considered in all energy and environment markets, Europe (including Eastern Europe) wide clearing of oil and gas markets, as well as Europe-wide networks, such as the Europe-wide power grid and natural gas network.

The fundamental design feature of ***PRIMES*** is its modularity. The model is organised by energy production sub-system (oil products, natural gas, coal, electricity, others) for supply and by end-use sectors for demand (residential and commercial, transports, six industrial sectors). The individual modules vary in the depth of their structural representation. The modularity feature allows each sector to be represented in a way considered appropriate, highlighting the particular issues important for the sector, including the most expedient regional structure. The electricity module covers the whole Europe, while representing chronological load curves and dispatching at the national level. The natural gas module also expands over the whole Europe. However, coal supply, refineries and demand operate at the national level. Furthermore, the modularity allows any single sector or group of sectors to be run independently as a debugging aid or for stand alone analysis.

At the global level, that is the market clearing level, the formulation of the model corresponds to a market equilibrium of the type:

Demand = Function (Price)

Supply = Demand

Price = Inverse Function (Supply)

$$
\text{Supply side:} \quad \left| \begin{array}{l} \min \; c\,x \\ \text{s. t.} \quad x \text{ in the set } X \\ \qquad Ax = q \end{array} \right.
$$

$$
\text{Demand side:} \quad q = Q(p)
$$

$$
\text{Cost Evaluation:} \quad u = f\,(c, x \text{ and other factors})
$$

$$
\text{Equilibrium Condition:} \quad p = u + \text{taxes}
$$

The behaviour in the supply side, corresponding to cost minimisation, is formulated as a set of linear programming models and the demand side has the form of a system of (non-linear) equations, hence the equilibrium model can be written:

Solve for x , q , p , u that satisfy:

where x and q denote supply and demand quantities, while u and p stand for producer and consumer prices.

The supply side may include more than one mathematical programming problem corresponding to the behaviour of several supplying agents (for example, one for refineries, one for gas and one for electricity). In addition, the possibility that some suppliers of energy commodities may also be demanders for other energy commodities (for example, the electricity sector) is included.

To solve the individual sub-models, ***PRIMES*** follows standard techniques, as appropriate to the mathematical form of each sub-model (mostly linear programming). To solve at the global level, an iteration process must be followed:

(i) one starts from an initial guess of the vector of energy prices;

(ii) then demand quantities are computed from the demand sub-models;

(iii) mathematical programming models for supplying agents are then solved to meet the computed demand;

(iv) based on the results of the supply sub-models, the cost evaluation equations compute producer prices, which augmented with taxes are used to evaluate new consumer prices;

(v) these are compared to the prices used in the previous iteration and if they are found close enough the process is terminated, otherwise the process restarts by re-computing demand.

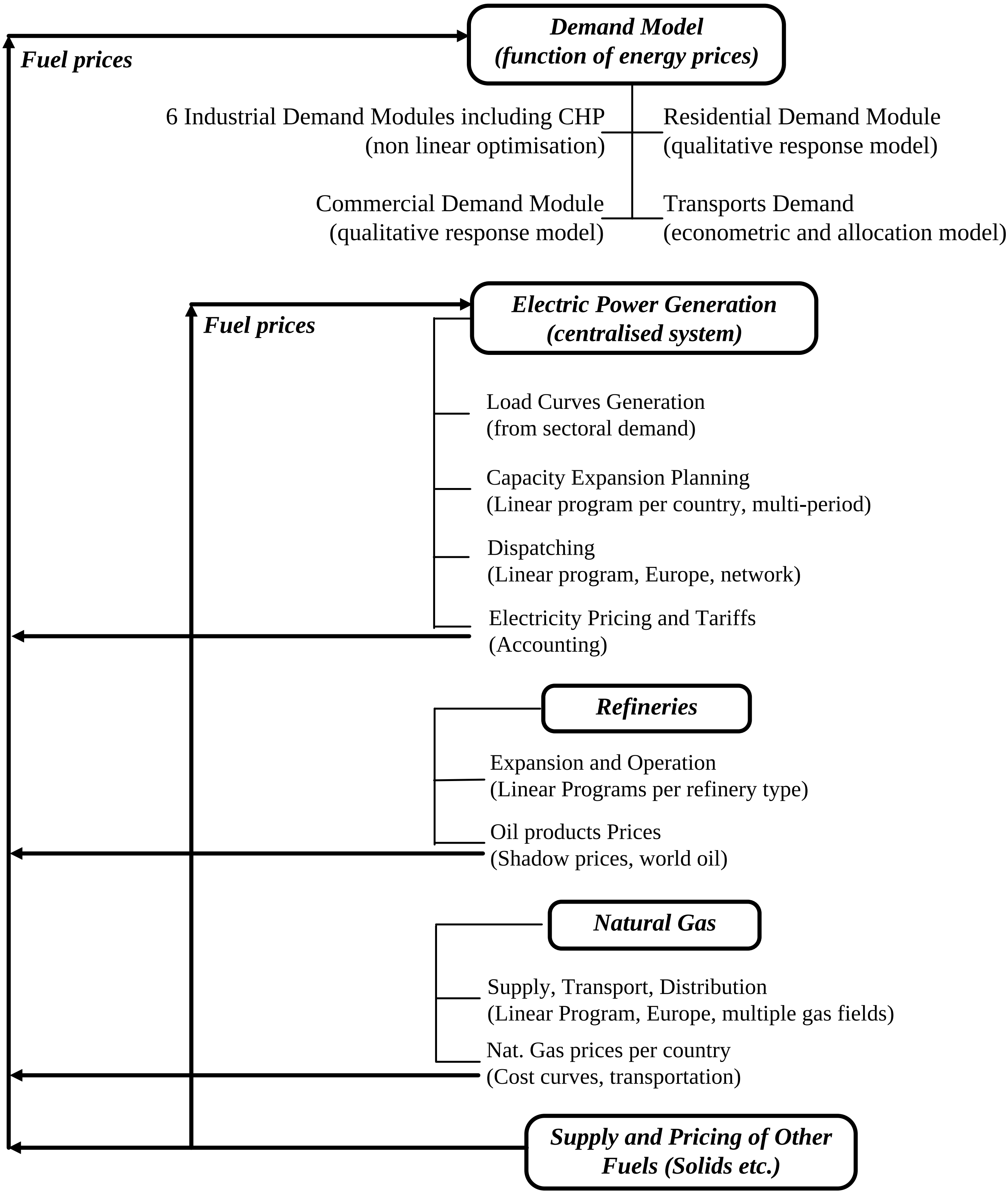
This is a Gauss-Seidel type of iteration.

The supply modules simulate both the operating and the capacity expansion activities. Thus, the model fully integrates a static and a dynamic solution. Dynamics are based on a backward looking anticipation mechanism (more formally, the model uses adaptive expectations).

Also, the model fully integrates the national within the multinational energy system (for gas and electricity). Demand is evaluated at a national level. Electricity dispatching and capacity expansion are determined at a national level, depending however on a complex market allocation mechanism, operating through the electricity grid, Europe-wide. The natural gas distribution market clears at a multinational level, even wider than the European Union. The refinery sector operates at a national level, but capacities, market shares and prices depend heavily on Europe-wide competition. Coal and lignite supply curves have, on the other hand, a national-specific character. Finally, energy savings, technology progress in power generation, abatement technologies and renewables are determined at each country-specific energy system.

Cost evaluation modules and price-setting mechanisms are at the core of the model. The former are attached to each energy supply module, and consider variable costs, fixed costs, investment costs and production efficiency, which enter either an average or a marginal costing system (depending on the sector). The price-setting mechanism reflects the design considerations for the market clearing regimes. Generally, four elements are considered: the supply costs, the world-wide leading prices (e.g. oil), the rental prices (for depletable fuels) and the competitor's prices (in some kind of competition). Given the modularity feature, the model formulates each market clearing regime as appropriate and, in some cases, alternate regimes to analyse structural features of the markets. The latter point is a way to study internal market issues.

3.4. General Model Scheme



3.5. Technologies and Environment

Particular emphasis is given to the representation of energy technologies and their development. Technology is considered explicitly in all demand and supply sub-models and integrated within the economic behaviour of agents. Technologies to abate pollution from energy activity are also included. Technological development is formulated through exogenous assumptions but also through market penetration logistic curves and learning-by-doing mechanisms.

The representation of atmospheric pollution and abatement is fully integrated in the model:

- policy instruments include taxes, standards and pollution permits;
- the economic behaviour of each supplier or consumer considers the environmental costs and constraints simultaneously with energy decisions;
- abatement technologies and stock-flow relationships are included in the sub-models;
- finally, emissions of CO_2, SO_2, NO_x and their concentration levels are also evaluated.

3.6. Model Nomenclature

The model is dynamic, solved by 5-years intervals and follows a time-forward path.

The simulations of the ***PRIMES*** model are performed using GAMS (General Algebraic Modelling System) and the SIGMA/NTUA modelling software. All sub-models of ***PRIMES*** are written in GAMS language and require a GAMS solver to solve. The handling of data, the global level convergence (markets) and the interactions between the sub-models are performed by SIGMA/NTUA Version 1.3, which also supports scenario simulation and reporting, all operating within the MS WINDOWS environment.

The general model nomenclature is presented in Table 2.

Table 2: ***PRIMES*** Nomenclature

Regions	• 12 European Union countries
Residential Demand	• 4 energy uses, types of households, 2 technology vintages, electric appliances
Commercial Demand	• 2 uses, 2 technology vintages
Industry Demand (6 models)	• iron & steel, non ferrous, chemicals, building materials, paper, other industries
	• 4 energy uses, 2 technology vintages, equipment categories, abatement equipment
Transports Demand	• 4 transport modes, 3 uses
Electricity Prod.	• 50 thermal generation technologies of which 10 new fossil fuel technologies, all renewables chronological load curves, interconnections special dispatching of renewables and CHP
Refineries	• 4 regions with typical refinery structure 6 typical refining units (cracking, reforming, etc.)
Natural Gas	• regional supply detail (Europe, Russia, Middle East, Africa, North Sea, ...)
Fuel types	• 18 energy types in total
Markets	• Country specific markets cleared European level markets: refining, gas, electricity exchanges World oil market: exogenous
Technology in Demand Models	• Technology Vintage Approach, Old and New, Logistic functions • In Industry, equipment types, e.g. boilers, furnaces etc., abatement technologies by use type
Power Generation	• Detailed treatment of new fossil fuel technologies, GTCC, IGCC, PFBC, ASFBC, fuel cells etc. • Consideration of dispatching constraints for the assessment of technologies and their prospects • Full representation of abatement technologies for SO2, NOx and implications of price-related environmental policy instruments

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