Invited Review

Energy models for planning and policy assessment

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The paper reviews energy models which have been applied to planning and policy assessment questions. It describes the history and methods of the early models, which had been developed for industrial purposes in the sixties. It illustrates how the scope of the model development and application changed during the seventies towards more universal applicable models of the total energy system and finally to models encompassing energy-economy interactions. The energy models applied today are mostly very large systems due to the complexity of the problems described. They consist sometimes of an integrated programming system, but in a few cases a set of disconnected models with different techniques are used.

A general survey of energy models is given with the purpose to present the broad categories of some of the well-known models in comparative form, discuss their content and application and provide a classification. A selection of three models which are typical representatives for particular categories is reviewed in detail and then follows an outlook for areas of future improvements.

1. Introduction

In the last decade, the question of future energy supplies has become one of the central political challenges in almost all countries of the world. Since the oil crisis in 1973 energy problems have moved to the core of the most difficult and controversial issues confronting society.

The radically increased public awareness of the energy problem has initiated a remarkably large number of energy policy studies and has given a substantial impetus to the development of energy models to help decision-makers deal with the broad variety of issues related to the energy problem. A large number of energy models have been developed all over the world and are now used for energy and policy planning purposes on a regional, national as well as on an international scale. The scope of energy models ranges from engineering models of different energy conversion technologies (e.g. refineries), sectoral models dealing with the demand and/or supply of single fuels, energy system models encompassing the entire energy system to models describing the energy system as an integral part of the overall economy.

This survey is not intended to give an exhaustive description of the energy models developed so far, or to evaluate the different methodologies applied in energy models. Rather, a limited number of representative models are described to illustrate the present state of the art. [1] Therefore, we will concentrate on energy system and energy-economy models for strategic planning and policy analysis. Before discussing specific models in some detail, we will give a brief overview of the history and methods used in energy modeling, and we will outline the nature of the issues facing the energy planner and energy policy-maker, which are characterized by complexity and uncertainty. The paper concludes with a discussion on unresolved modeling issues and some recommendations on how to improve the usefulness and impact of energy models in energy policy and planning.

2. Energy models: history, methods and application

The history of energy modeling goes back some twenty years to the 1960's. Although efforts to

[1] For further information we refer to the following general reviews of energy models [1-8] and to the major conferences held on energy modelling [9-13].

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develop energy models began well before the first oil crisis in 1973, it was the growing awareness of the energy problem originating from this event that forced an explosion in the development of energy models. Exact figures concerning the energy models developed so far are not available, but in the reviews of energy models published by the International Institute for Applied Systems Analysis (IIASA) [1,2,3] up to 1976 alone some 144 different models were characterized and classified. The individual models vary greatly in their objective, addressing a broad scope of problems for geographical areas of widely different sizes and they employ a variety of methods originating from several scientific disciplines.

The energy models developed in the sixties focused mainly upon the supply and demand of a single energy form or fuel like electricity, oil or natural gas. Faced with the complex problem of optimal allocation and routing of crude oil and oil products between different oil sources, refineries and demand centers the petroleum companies have developed and applied particularly large allocation models, as well as models for the refining process [14]. Another example of a successful application of models, of the sectoral type, are the models used for the analysis of electric utility operations and expansion plans. A large number of models have been developed and are used to evaluate the optimal expansion strategy of the power plant system required to satisfy an increased electricity demand [15,16,17]. The models determine the optimal mix and timing of new power plants of different types so that the electricity demand over the planning horizon is satisfied at minimum discounted overall cost, including capital, fuel, as well as operating costs.

Both types of models mentioned above focus on the supply side, that is, on the best way to satisfy an assumed energy demand. Energy demand is an exogenous input to these models and is often provided by econometric demand models, estimating energy or fuel demand as a function of energy prices and other determinants such as population, economic growth, etc.

A major criticism made of sectoral, single fuel or energy form models is that they treat the development of the sector or fuel in question as in isolation from the rest of the overall energy and economic system, thereby ignoring that there are many different ways to satisfy given energy service demands such as space heat, industrial process heat, and transportation. A sectoral, single fuel model cannot adequately describe the *interfuel substitution* related to changing energy prices, technological development or environmental considerations in the different sectors of energy use.

Complying with these requirements was the main reason for the development of *energy system models*, describing the energy flows from different primary energy sources through various conversion and utilization processes to different end use demands. It was at the beginning of the seventies, when the work on energy system models began.

A national energy balance as shown in Fig. 1 can be viewed as a simple static model of the energy system, because it accounts at a single point in time for all energy flows from the primary energy sources, through conversion processes, to the ultimate use of various fuels and energy forms.

Most of the energy system models are based on the network representation of the energy balance approach. Using this network of flow of resources (coal, oil, gas, nuclear, solar) to various demand sectors (industry, transportation, commercial, household) as a simple accounting framework, the consequences of alternative ways to satisfy an estimated demand development in each of the major end-use sectors can be simulated and evaluated in terms of primary energy consumption, required conversion capacity etc. Extensions of this type of model to analyse the impact of alternative energy supply strategies on the environment and in terms of energy cost are easily attainable and have been used in the past [18].

Besides these network accounting models, a series of optimizing models of whole energy systems were developed from the beginning of the seventies [19,20,21,22]. These models were designed to determine the optimal allocation of energy resources and conversion technologies to end-uses using the network representation of the energy system. The models are either static with the optimization process seeking a minimization of cost for a single target year, or they are quasi dynamic and attempt to minimize the present values of the cost over the whole planning horizon, subject to the demand and to a set of constraints reflecting resource availabilities and/or environmental considerations.

Accounting and optimization models of this type focus on the technical structure of the energy

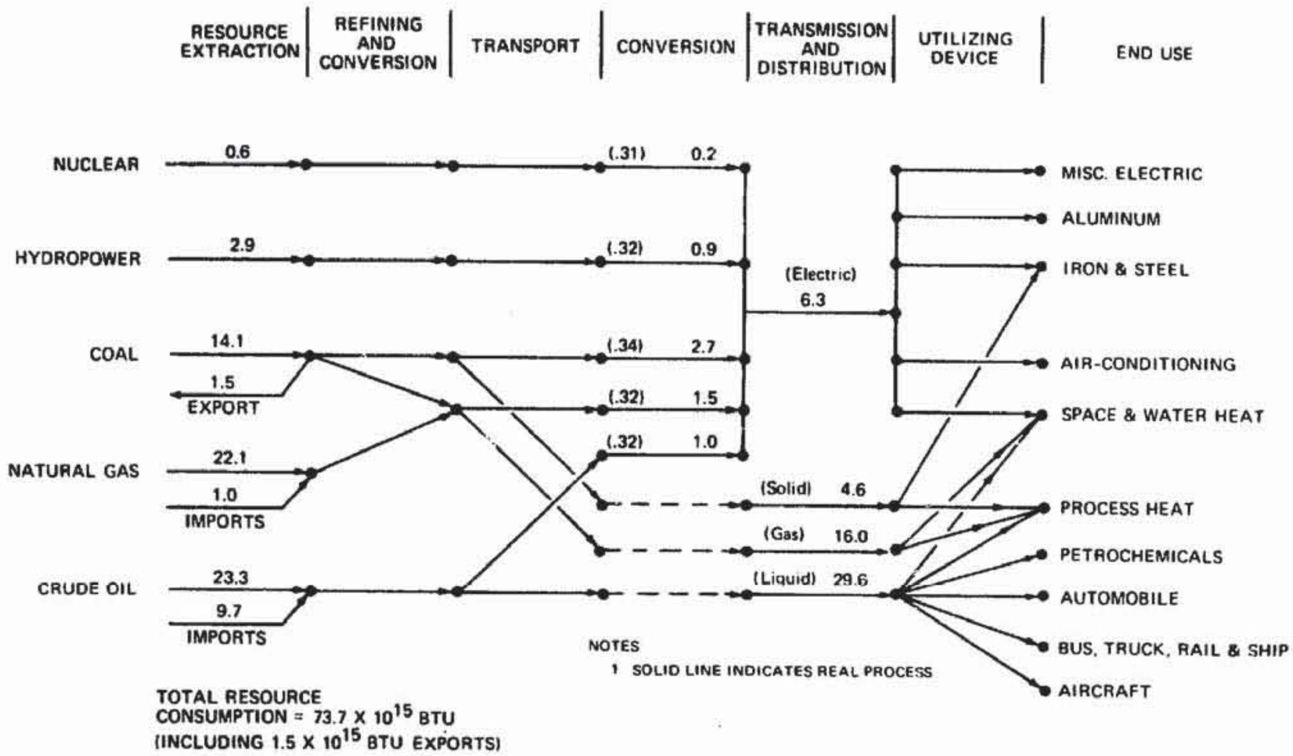

Fig. 1. National energy balance [41].

systems and an energy demand is usually an exogenous input to them. With demand as a fixed input, these models do not allow for demand adjustments due to higher energy prices or to changed GNP growth caused by rising energy cost and limited energy supplies.

Handling these issues requires models linking the energy sector with the rest of the economy. Most of the recent energy modeling work is devoted to this area of energy-economy interaction [9,12]. Various approaches to link economic models to models of energy demand and supply are currently being investigated. We will discuss some of this in Section 4, when we describe a number of models in more detail.

This short glance back into history should show that, although the construction of energy models began only 20 years ago, there have been several important development phases as sectoral models evolved towards models of complete energy systems and energy-economy models.

Of course, improvements were also made in methodology, although one must state that the development of new and better methods was not the main goal of the development of energy models, but rather that the energy model builder referred essentially to the corresponding improvements and developments of other fields of science, e.g. econometrics, statistics, operations research, computer science, and systems science. Looking back, one can also say that there are three modeling methodologies that have been applied dominantly in energy models, namely engineering process analysis, mathematical programming, and econometrics. Econometric methods are found most often in representations of the energy demand side emphasizing the behavioral aspects of decisions on the sides of both the consumer and the supplier. Statistical techniques are used to estimate the structural parameters of the behavioral equations, e.g. macroeconomic production functions or price elasticities from observed data. Econometric models are, in general, of a higher aggregation level than process models, which often cover quite a lot of technical details of the energy supply system. This is independent of whether it is conceived as simple accounting or as an optimization model. The linear programming technique has been used far more than other mathematical programming methods because of its capability to solve large problems. Linear programming models formulated in terms of energy quantities flowing through the energy system provide, via the shadow prices, useful economic information about the optimal solution.

In addition to these methods, energy models were also occasionally developed which make use of the input–output method, the system dynamics approach or the methods of game theory.

In the following, some illustrative energy models will be discussed in more detail. We will confine ourselves to models which deal with the complete energy system or the interaction between the energy system. Before describing particular models, it is necessary to first review, in the next section, the main aspects of the energy problem, the nature of energy planning and policy questions, and the need for decision-making aids such as energy models.

3. Energy planning and policy issues: complexity and uncertainty

The development of energy models is not an end in itself, rather it is only justifiable when it attempts to provide a contribution to the solution of the pressing energy problem. In order to make clear which demands and problems planners and policy makers are confronted with and what contribution energy models can have, we consider it necessary to combine an overview of the development and the present state of energy models with the description of some details of the energy problem itself.

Today it is recognized throughout the globe that the world is faced with a serious energy problem. It is generally agreed that the central problem for most countries over the short and medium term consists in coping with the dramatic rise in oil prices and the existing dependency on crude oil imports. In the longer term, the persistent and dominant question is, which energy sources can and should guarantee the energy supply in the light of the foreseeable exhaustion of crude oil and natural gas reserves.

Although there exists an extensive consensus on the severity of the present energy supply situation, opinions and views differ widely as to the appropriate path towards a post-petroleum energy supply system and as to which primary energy carrier should have priority in substituting for crude oil and natural gas. Some see an increased use of coal and the building-up of nuclear energy as the solution to the problem, while others support conservation by more effective energy end-use. Still others believe that a decentralized use of renewable energy sources alone can represent a long-term solution capable of bearing the load. Besides technical and economic arguments there are especially questions of environmental protection, security, the proliferation of nuclear weapons as well as general political aspects which mark the energy discussion. The emotional and controversial energy discussion is also a reflected image of the problems which confront those active today in the field of energy policy or energy planning. Complexity and uncertainty are its characteristic attributes.

In the field of energy production, conversion, transport, distribution, and end-use technology, there is a wide range of technical constraints and specific features of respective technologies to consider in order to guarantee compatible interaction with the other components of the energy system. A plurality of new technologies, e.g. coal refinement or the use of renewable energy sources, are under development today. Their timing of commercial introduction, their costs, and their technical parameters, such as efficiencies, can be stated today only with a large range of uncertainty. Also, the interactions between the energy system, the other sectors of the economy, and the general economic growth are complex and only inadequately known today. The consequences of rising energy prices or of a limited energy supply on the economic development are essentially aspects which must be taken into consideration within the scope of energy-policy decisions. Considerable uncertainty also exists with regard to the future development of energy requirements. This arises on the one hand, because a further economic growth is no longer seen automatically as desirable, and on the other hand, because it is hard to anticipate to what extent energy-saving measures and methods will be carried out. Availability and price development of crude oil, acceptance of nuclear energy, global environmental problems (e.g. CO_2) are only several of a number of important issues giving rise to the complexity of the energy problem as well as to the considerable uncertainty, under which energy-policy decisions must be met.

All this means is that the energy-policy planning process has entered an era of new complexity and clouded futures. Rather than asking what the energy demand in some future year will be, or what the contribution of different supply options will be, a better question is, "what must an energy policy look like, if it is to be robust and flexible enough to cope with the uncertainties that lie ahead?"

If energy models are to aid in decision-making, then it cannot be a meaningful aim to forecast the future development of the energy system. However carefully the forecast is made, the inherent uncertainty lying in the future cannot be removed. Rather the task consists in showing, after explicit consideration of the uncertainties and the technical and economic options, the 'robust' steps. These are decision steps relevant to the immediate future and give the best possible guarantee that the path chosen will not have been regretted at a much later point of time.

Finally, it should be remarked, that in view of the complexity of energy policy and energy strategy issues, no model can give answers to all the questions. Rather, it will require several models with different objectives and specifications in order to effectively support the development of energy policies and energy planning.

4. A survey of energy models

Energy models are developed using theoretical and analytical methods of several disciplines: engineering, econometrics, operations research, computer sciences. Because of this, and the differences in scope and application, there is no unique way for the design of such models.

The purpose of this survey is to present the broad categories of such models in a comparative form, discuss their content and application and provide a classification. The survey is not supposed to be exhaustive in that it provides comparative information on all existing models. In our classification, we limit ourselves to typical candidates known in the literature, while a selection of three models is reviewed in a more detail.

Table 1 lists several of the well-known models together with the methodology and their principal application. Two classes have been distinguished: models of the energy system and models representing the energy sector and its interactions with the rest of the economy. These energy-economy models are either built in the form of an integrated modeling framework or employ a set of more or less disconnected models. An example is selected from each of these three categories and examined in more detail below.

4.1. MARKAL

MARKAL (an acronym for market allocation) is designed to assess the long-term perspectives of new and conservation technologies and thereby provide insights for research and development support. It is a multi-period linear programming model with explicit representation of some 200 technologies for energy production, conversion and end-use.

The specific aspects which the model helps to analyse are:

- the relative attractiveness of existing and new energy technologies and energy resources in satisfying plausible future demands for useful energy;
- the time evolution of the introduction of and investment costs for new technologies and resources and the time evolution of the decline in use of existing resources, especially imported petroleum;
- the sensitivity of future energy systems to different policy objectives, with system cost, the amount of imported petroleum, and the relative contributions of nuclear, renewable, and fossil resources being the criteria of interest; and
- the long-range effect of conservation and efficiency improvements on the energy system.

MARKAL was developed in a collaborative effort at Brookhaven National Laboratory, USA and Kernforschungsanlage Jülich, Germany, building upon earlier experience with BESOM and other LP-models. For a complete documentation see [32,33].

The intent for the development was to evaluate energy R&D priorities for the group of countries belonging to the International Energy Agency [34]. Because the quantitative assessment had to be done on a national basis for 15 individual countries, a very flexible model of the energy system with standardized input and output routines had to be built. The model allowed all countries to use the same basic set-up, while technologies representing virtually all levels and modes of production, conversion and end-use were represented. The optimization of the supply paths *and* the

Table 1
A survey of energy models

		MODEL	METHODOLOGY	APPLICATION
ENERGY SYSTEM MODELS		BESOM (Brookhaven) [19]	Linear Optimization	Evaluation of energy technologies for US R&D policy.
ENERGY SYSTEM MODELS		EFOM (Grenoble) [20]	Linear Optimization	Originally built to develop energy scenarios for France. Now used within the CEC set of models for policy assessment.
ENERGY SYSTEM MODELS		MARKAL (Brookhaven/Jülich) [21]	Linear Optimization	Optimization of end-use and supply side. Applied to 15 countries of the IEA for evaluation of new and conservation technologies.
ENERGY SYSTEM MODELS		MESSAGE (IIASA) [22]	Linear Optimization	Applied to 7 world regions in the context of IIASA's set of models.
ENERGY-ECONOMY MODELS	INTEGRATED MODELS	ETA-MACRO (Stanford Univ.) [23]	Non-Linear Optimization, Informal Econometric	Studies of nuclear and alternative energy systems in the US.
ENERGY-ECONOMY MODELS	INTEGRATED MODELS	PILOT (Stanford Univ.) [24]	Dynamic Linear Optimization	Exploration of energy and economy growth in the US.
ENERGY-ECONOMY MODELS	INTEGRATED MODELS	SRI (Stanford Res. Inst.) [25]	Process Representation, Informal econometric	Analysis of US synfuels strategy.
ENERGY-ECONOMY MODELS	INTEGRATED MODELS	HUDSON-JORGENSON [26]	Econometric	Longterm energy and economic growth analysis of the US. Taxing policy in the US.
ENERGY-ECONOMY MODELS	INTEGRATED MODELS	ESPM (Bechtel Co.) [27]	Accounting	Framework for energy supply planning and accounting of industrial, capital, labor and material requirements. Applied to the US and developing countries (Peru, Egypt, Indonesia).
ENERGY-ECONOMY MODELS	INTEGRATED MODELS	PIES (Project Independence Evaluation System) [28]	Process Representation, Linear Optimization, Econometric	Analysis of alternative strategies for the national energy plan of the US.
ENERGY-ECONOMY MODELS	MODEL SETS	DRI-BROOKHAVEN [29] (combination of Hudson-Jorgenson and BESOM models)	Linear Optimization, Econometric	Studies of economic impact of alternative energy futures in the US.
ENERGY-ECONOMY MODELS	MODEL SETS	CEC (Brussels) [30] (combination of macro-economic growth, energy demand, input-output and energy supply models)	Linear Optimization, Econometric	Application to member countries of the European Communities for Energy System Studies.
ENERGY-ECONOMY MODELS	MODEL SETS	IIASA (Laxenburg) [31] (combination of macro-economic, energy demand, energy supply and energy impact models)	Linear Optimization, Econometric,	Applied to studies of the energy-economy growth of 7 world regions. Investigations about energy strategy impacts.

end-use paths in MARKAL is perhaps the most prominent difference to other LP-models shown in Table 1. All of the other models optimize only the supply paths for a given end-use pattern.

Fig. 2 shows the principal energy flows represented in MARKAL. Three types of energy are distinguished in the diagram: through conversion, transportation and distribution, primary energy

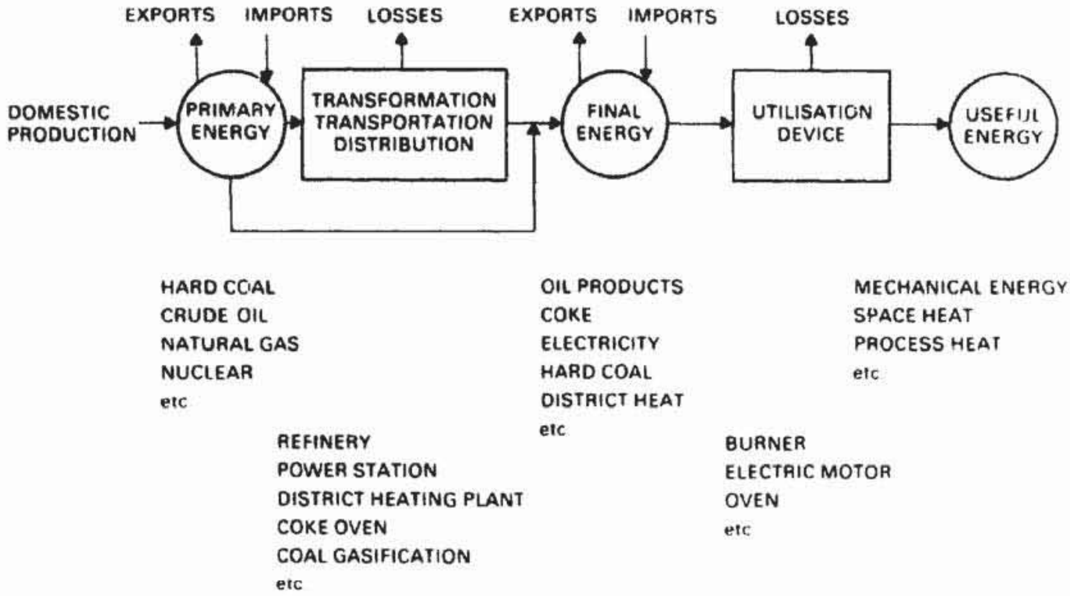

Fig. 2. The MARKAL energy system [34].

(e.g. domestic coal, imported crude oil) is transformed into final energy (e.g. electricity, refined oil products, district heat), which is then consumed in end-use devices to produce useful energy (e.g. space heat, mechanical energy). Useful energy is the exogenously specified driving variable in MARKAL.

MARKAL is, like MESSAGE and EFOM, a multi-period model, i.e. a model with several distinct time intersections for which an optimum allocation of the energy and technology mix is made. This representation is of major importance when analyzing the time aspects of the transition to new technologies and it is another difference to the static LP-models represented by BESOM in our list.

MARKAL allows for a variable number of periods and period lengths, but it has normally been applied to 9 time periods of 5 years, which are centered at 1980, 1985 etc. through to 2020. Each of the technologies represented in the model is described in terms of an activity and capacity variable. The capacities depend on investments made in earlier periods and the defined lifetimes of existing technologies. Because of this representation, the model is able to describe the phasing out of existing plants and the build-up of new capacity properly. The electricity and district heat generating technologies have been modeled in MARKAL with explicit treatment of the load structure related to the diurnal and/or seasonal variations of the demand. Care is given to cost for transportation and distribution of energy.

The number of technologies, which are represented in national applications of MARKAL, each with associated costs, efficiencies, lifetimes, etc., is quite large. Table 2 shows a list of the generic technologies.

A typical result obtained from MARKAL is shown in Fig. 3, indicating how the substitution of oil imports by new liquid fuel producing technologies takes place under a certain price escalation for crude oil.

Another set of interesting information, which MARKAL provides, is the trade-off between energy system costs and oil imports, as displayed in Fig. 4. The curve shows what a replacement of oil imports would cost the economy, which would have to invest in new technologies or push conservation. In the figure, PS-1 denotes the optimum allocation of fuels and technologies for a least cost scenario. If we move towards the left, the system costs increase, while oil imports decline. The fact that a premium is to be paid for lower oil import energy systems is denoted by scenarios SP-1/PREM-1 and SP-1/PREM-2. Three different patterns are shown (Spain, United States, United Kingdom) illustrating differences among countries.

Each point on this trade-off curve represents a scenario, which itself yields a different mix of technologies and a different temporal evolution for each technology. Other trade-offs, e.g. between

Table 2
Generic technologies selected for assessments with MARKAL

END USE	CONVERSION
CONSERVATION-AUTOMOTIVE TRANSPORT SYSTEMS - Private Auto, Improved Frame and System - Private Auto, Improved Diesel - Private Auto, Stirling Engine ALTERNATIVE TRANSPORT FUELS - Private Auto, Methanol Fuels - Compressed Natural Gas CONSERVATION BUILDING (EQUIPMENT) - Electric Heat Pump - Gas Heat Pump - Seasonal Low-Temperature Heat Storage, Underground ELECTRIC AUTO - Battery-Powered Auto INDUSTRIAL CONSERVATION - Solar to Process Heat - Atmospheric Fluidized Bed Industrial Boiler for Process Heat RESIDENTIAL AND COMMERCIAL SOLAR HEATING - Space Heat - Water Heat - Air Conditioning **PRODUCTION** ENHANCED GAS RECOVERY ENHANCED OIL RECOVERY GEOPRESSURIZED METHANE GEOTHERMAL/HYDROTHERMAL/HOT DRY ROCK - Dry Geothermal (Hot Rock) Power Plant - District Heating Plant, Geothermal OCEAN POWER - Wave Central Electric Power Plant - Ocean Thermal Gradient Electric Power Plant SHALE AND TAR SANDS SOLAR ELECTRIC - Decentralized Solar Photovoltaic - Central Solar Thermal Electric - Central Solar Photovoltaic Plant WIND POWER - Wind Turbines, Central Electric Power Complex - Local, Wind Electric Generator	ADVANCED CONVERTER REACTORS - ATR Nuclear Power Plant - CANDU Nuclear Power Plant, Enriched Fuel - HTR Nuclear Power Plant - Nuclear Process Heat, VHTR BREEDER REACTORS COAL LIQUEFACTION - Hydrogenation - SRC-2 Process - Methanol COMBINED CYCLE - Hard Coal Combined Cycle Power Plant - Pressurized Fluidized Bed Power Plant - Atmospheric Fluidized Bed Power Plant FUEL CELLS - Gas Fuel Cell FUELS FROM BIOMASS - Biomass Steam Electric Power Plant - Methanol from Wood - Gas from Wastes FUSION - Nuclear Fusion Power Plant HIGH CALORIC GASIFICATION - High Btu Gasification, LURGI-Slagging - Nuclear Hydrogasification LOW-MEDIUM CALORIC GASIFICATION - Hard Coal, Medium Btu Gasification - Hydrogen Production from Hard Coal MAGNETOHYDRODYNAMICS - Coal MHD Electric Power Plant NON-FOSSIL HYDROGEN SYSTEMS - Hydrogen Production by Electrolysis of H_2O UNDERGROUND GASIFICATION - Underground Gasification with Combined Cycle Electric Power Plant

costs and environment can be examined in a similar approach. The example illustrates that MARKAL is a multi-objective function model, which in fact can be used as an analytical instrument to study essential relationships in the energy sector and provide information on a cost-benefit scale.

Fig. 5 illustrates how MARKAL can be used

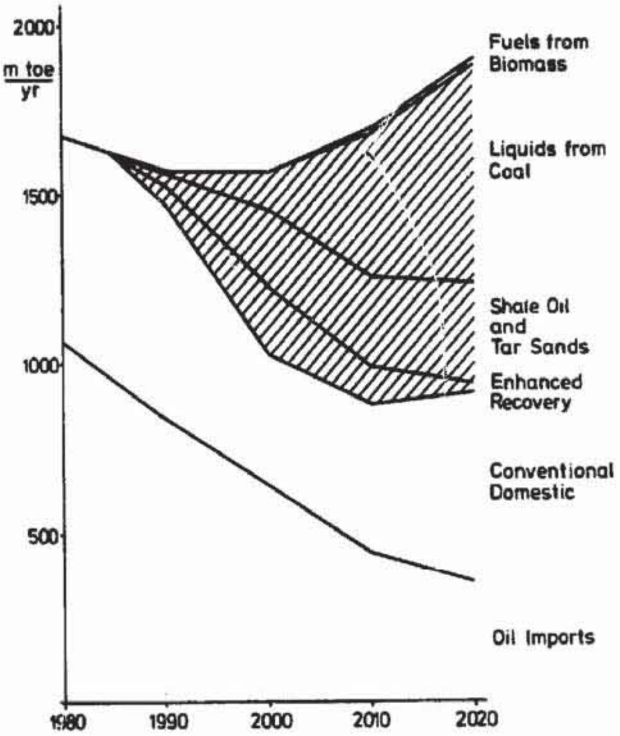

Fig. 3. Liquid fuel supply in the IEA countries [34].

for technology assessment under the aspect of uncertainties. It shows how the market penetration of a particular technology takes place in a comparison of six distinct scenarios denoted with P1, P3, P6, S5, S8 and R1. These are scenarios with different objective functions and/or input data. The result of the analysis is that the technology gains a high share of the market between 1980 and 2020, with a peak at the year 2000 in all of the scenarios, i.e. this infers that the particular technology is a stable candidate from a suppliers and consumers point of view. These types of analyses have been found to be useful aids for energy R&D program planning [35,36,37].

Further extensions of MARKAL have been made focusing on specific areas of interest to policy assessment and planning. For instance, detailed analyses of the residential and commercial conservation possibilities have been made [38] and the application of the model on the level, which is suited for community energy supply planning, has been initiated [39].

Another extension of the model which is planned for the future aims at incorporating demand price elasticities. This means that the response to energy price increases will be determined by the model in three forms: investments in conservation, investments in new technologies and adjusted useful demand levels. This extension will

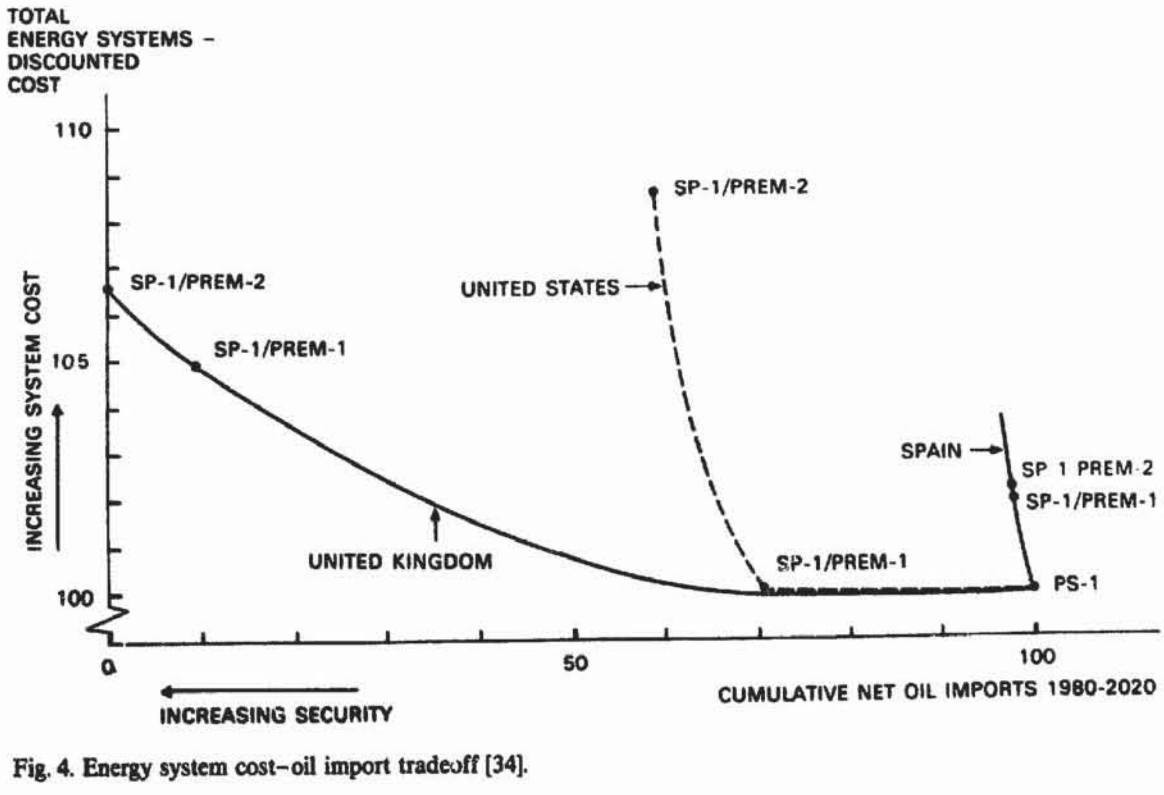

Fig. 4. Energy system cost–oil import tradeoff [34].

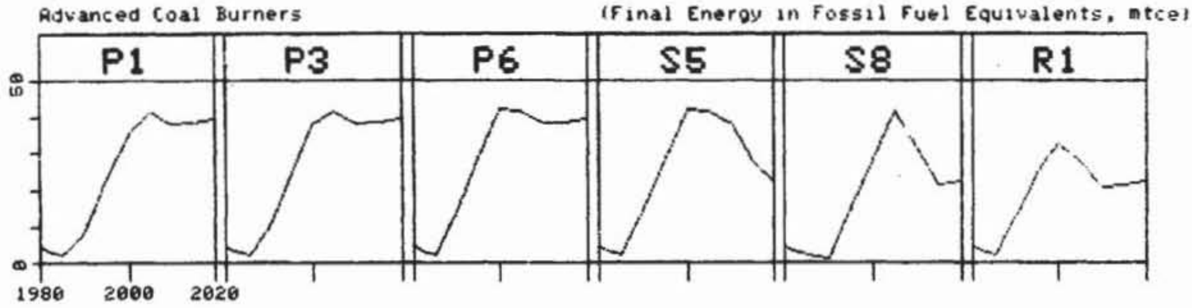

Fig. 5. Comparative analysis of 6 MARKAL scenarios: 1980–2020 market penetration of advanced coal burners for industrial applications in Germany [35].

result in a model type, which is often called a partial equilibrium model, where energy demand itself is a variable depending on the price of energy.

4.2. ETA-MACRO

ETA-MACRO is an example of the second category of models contained in Table 2, i.e. those which are designed to study the interactions between the energy sector and the rest of the economy. If is in fact, as the name suggests, an integration of two models: ETA is a process analysis for energy technology assessment, and MACRO is a macroeconomic growth model dealing with substitutions between labor, capital and energy inputs. Fig. 6 contains the principal linkages between the energy and the macroeconomic submodels.

Note that the main feedback of information between the two parts is via parameters specifying the amount to which energy (separated for electric and non-electric form) is required as an input for the production of a unit GNP, and the energy expenditures that the economy is willing to pay.

The entire model determines for each point in time an equilibrium between supply and demand, whereby substitution between labor, capital and energy input take place according to their availability and price. An increase in prices for energy will then affect the future level of energy demand, the fuel mix and the production structure of the economy in various ways. Price induced conservation and interfuel substitution will both have macroeconomic implications and the whole economy will adjust to a new equilibrium according to the time lags built into the model. This model is of the type which may be called a 'general equilibrium

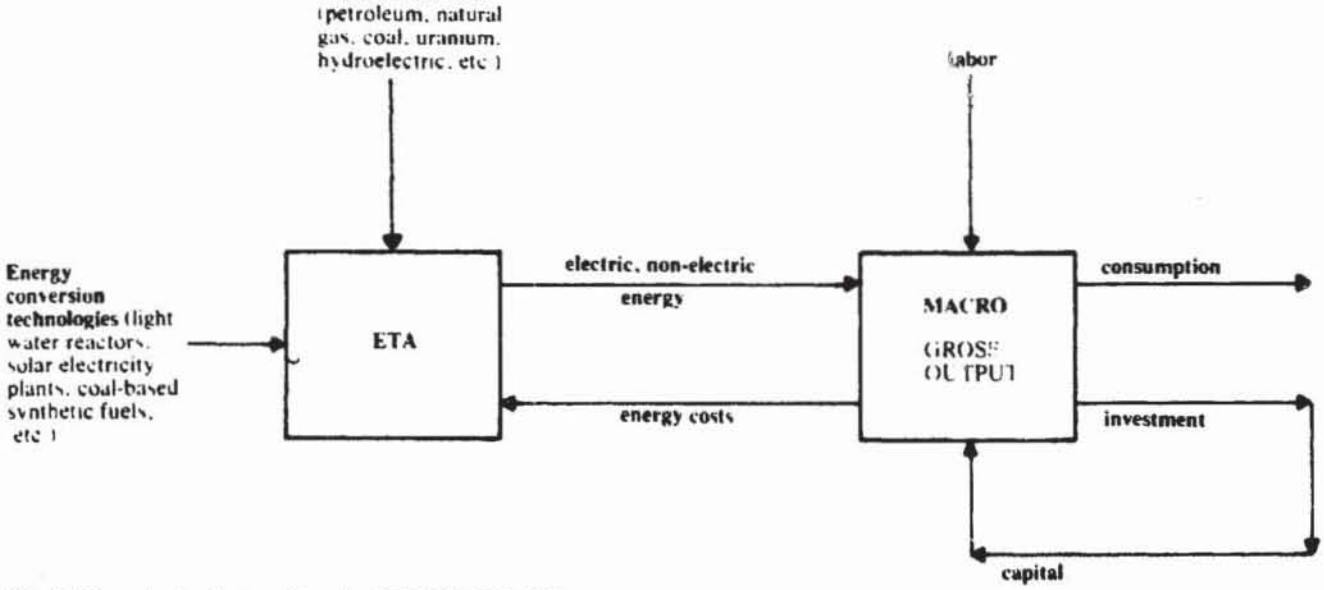

Fig. 6. The principal interactions in ETA-MACRO [23].

model', in that it encompasses at the same time the effects which the macroeconomy has on the energy system and vice versa the impacts of the energy system on the economy.

To be able to understand how the model works, it seems best to have a closer look to the MACRO submodel. A key equation of the model is that describing the production function assumed.

The production function employed assumes that the economy-wide gross output (Y) depends upon four inputs: K, L, E, N—respectively capital, labor, electric and non-electric energy. The elasticity of substitution among the input factors is separated in three fractions: substitution between capital and labor (denoted by α and $1-\alpha$), substitution between electric and non-electric energy (denoted by β and $1-\beta$), and substitution between capital/labor and electric/non-electric energy (denoted by σ). If we were considering a static problem, the long-run production function would then be written as:

$$Y=\left[a(K^{\alpha}L^{1-\alpha})^{\rho}+b(E^{\beta}N^{1-\beta})^{\rho}\right]^{1/\rho}$$

where $\rho=(\sigma-1)/\sigma$ (for $\sigma \neq 0,1,\infty$). (The parameters a and b are empirical constants).

In ETA-MACRO the situation is more complex since it allows for time-lags in the economy's response to higher energy prices: A 75 year planning horizon is introduced, starting with 1975 and extending through 2050. There are 16 individual time periods, each of five year length and centered at a representative year: 1975, 1980, 1985, etc. The introduction of the time variable appears to be extremely important when we consider the transition to less energy intensive economies. Time is required for life-styles and for capital stocks to adjust to higher energy costs, etc.

In ETA-MACRO these lags are built into the production function by appropriate growth limitations relative to previous periods. Note that the production function is non-linear in type. All other equations used in ETA-MACRO are linear combinations of variables.

Other principal equations of the macro submodel describe the growth of the capital stock, the allocation between consumption, investments and energy expenditures and the savings process.

The other submodel, ETA, is a conventional linear programming energy demand-supply model, which for a given set of resources and technologies aims at building an optimum energy path. The degree of detail shown here, however, is much less than in energy system models of the MARKAL type.

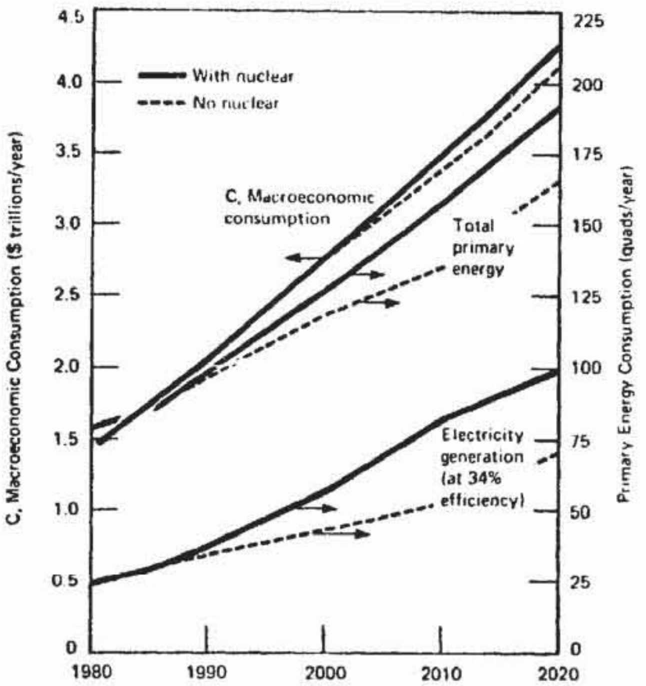

Fig. 7. Macroeconomic consumption, primary energy and electricity generation in a nuclear and a non-nuclear US economy [15].

As most of the general equilibrium models which apply aggregated functions for the economy and look into the energy sector with less detail, ETA-MACRO is not intended to be used as a *planning tool*, which produces a single set of numerical results. The merits of the model lie in the fact that it enables us to check the logical consistency of competing assumptions about energy futures using a clear and straightforward approach. In fact, the model has been found to be a useful instrument to study for instance the implications which a non-nuclear path would impose on the US economy. Fig. 7 illustrates this case indicating what a stop on nuclear energy would cost the economy in terms of GDP losses. Other examples showing how ETA-MACRO permits the exploration of macroeconomic issues which are of principal interest to energy policy and technology assessment are contained in the literature.

4.3. IIASA's set of energy models

The energy modeling approach of IIASA (the International Institute for Applied Systems Analysis) is another typical example for the energy-economy models. It is designed to analyse the energy sector as an integral part of the economy.

But unlike the integrated models (PILOT, SRI, Hudson–Jorgenson, ETA-MACRO), which treat the interactions between energy and the economy within a single network of equations, IIASA has created a package containing a set of various models, applying different techniques.

IIASA's energy modeling team has adopted the philosophy that the linking of several independent and simple models has advantages over large scale model blocks involving complex functional relations. The links need not be automatic, but may involve human interference. Other modelers (like DRI-Brookhaven, CEC, for instance) have followed a similar model set approach by using well established independent models of the energy sector and the economy in a combined assessment.

Fig. 8 illustrates the modeling approach adopted at IIASA. Four independent models, MEDEE-2, MESSAGE, IMPACT and MACRO, each applying a different methodology and having a different purpose, are used. Each model provides inputs to the system considered, either in the form of direct input data to other submodels or in the form of general information which goes into judgements or into manual calculations and other assumptions. The entire modeling approach is a highly iterative one. Initial assumptions and judgements lead to calculations and results, which provide feedback information for the alteration of the inputs, until convergence is achieved.

The start of the modeling loop is determined by the definition of scenarios as indicated on top of Fig. 8. Assumptions about economic and population growth are the main parameters for the distinction of the IIASA scenarios. Information about economic and demographic developments and judgements about lifestyle changes, improvements in efficiencies of energy using devices, and the rate of penetration of new and/or improved

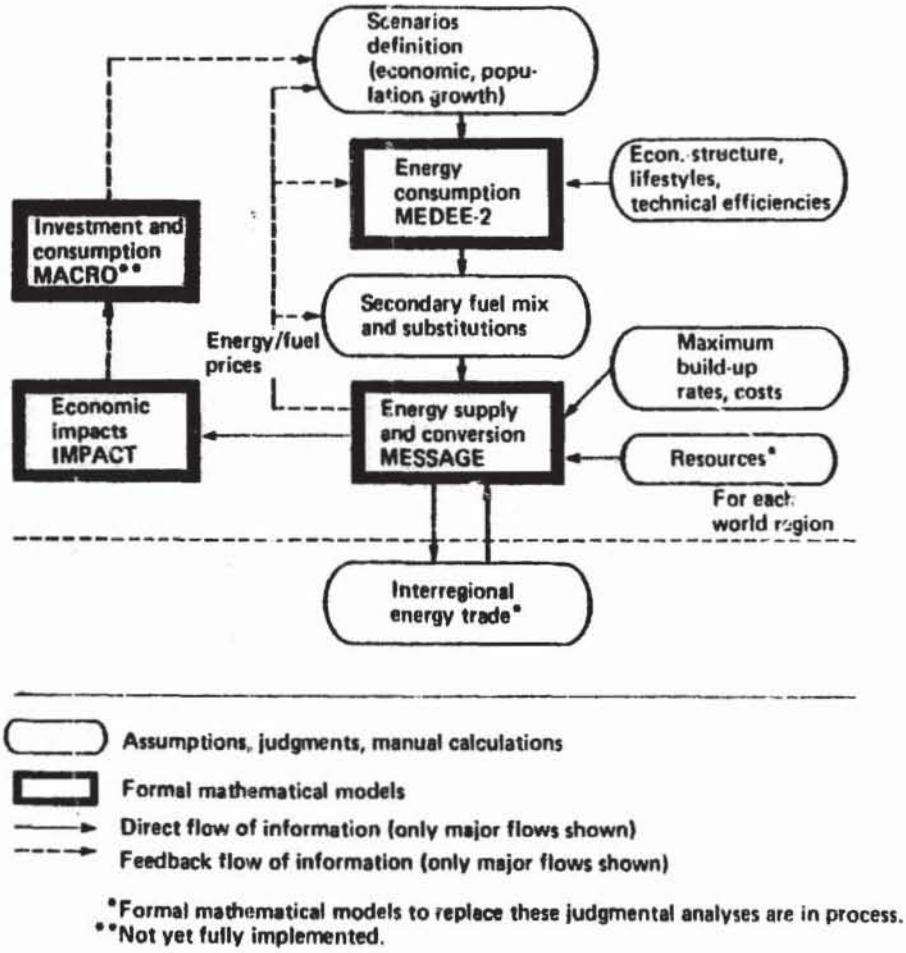

Fig. 8. The IIASA set of energy models and the model linkages [31].

energy-using equipment are fed into the submodel MEDEE-2 (Modèle d'Evolution de la Demande d'Energie). This model determines the energy demand in terms of secondary energy for major end-use categories such as space heating/cooling, water heating, cooking in the residential and commercial sector or space and water heating, low and high temperature steam generation and furnace operation in various industries etc. The degree of detail in the demand vectors permits the description of substitutions on the end-use side.

The technique of MEDEE-2 is simple: most of the relationships are linear combinations of variables and the model is used as a straightforward accounting framework. The resulting secondary fuel mix together with constraints on the maximum build-up rates, cost of new energy supply and conversion facilities and resource availability constraints, is then inserted into the second submodel, called MESSAGE (Model for Energy Systems And their General Environmental impact). MESSAGE is, like MARKAL, a time-dependent linear programming model which provides an optimum allocation of fuels to meet a given demand. It is a dynamic model and allows the explicit treatment of interfuel substitution, which takes place over time in the energy supply and conversion sector.

The third submodel, IMPACT, is a dynamic input–output based algorithm, which determines the impacts of a certain strategy on the economy in terms of:
- investments in energy system capacities;
- capacity build up in energy related sectors of the industry and corresponding capital investments;
- requirements for materials, equipment and services for construction and operation of the energy system and related industrial branches.

With IMPACT calculated costs, the economic feasibility of a strategy can be checked, e.g. whether or not energy will absorb unacceptably high portions of the economic products, or what amount of non-energy exports are necessary to compensate for energy imports, or which capital aids are necessary for a developing country, etc. Finally, the MACRO submodel, the structure of which resembles the macro-economic part of ETA-MACRO, calculates aggregated investment and consumption patterns based upon IMPACT provided cost data. This in turn leads to a revised computation of economic growth rates, which is checked with the original assumptions and reentered into a new iteration loop.

It is this very broad concept of iterations within the computation routes which provide for consistent scenarios. If the full set of models are employed in iterations, we have in fact a general equilibrium approach for interactions between economic and energy sector activities.

IIASA's energy modeling set is not designed for energy planning purposes but aims at investigating the *longer term perspectives for transitions* to energy supply systems in a resource constrained world. It has been applied to a study of the development of world regions between now and

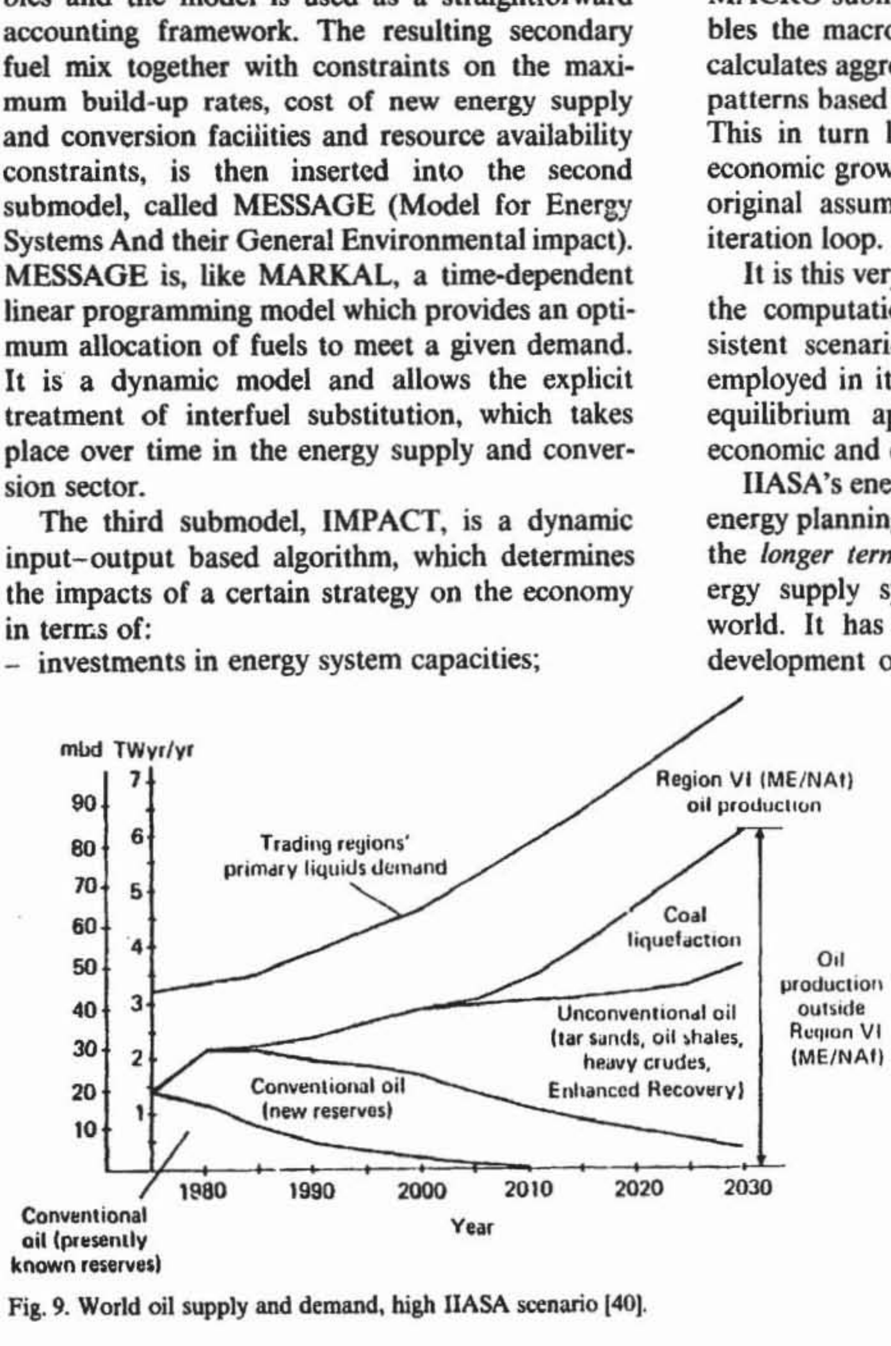

Fig. 9. World oil supply and demand, high IIASA scenario [40].

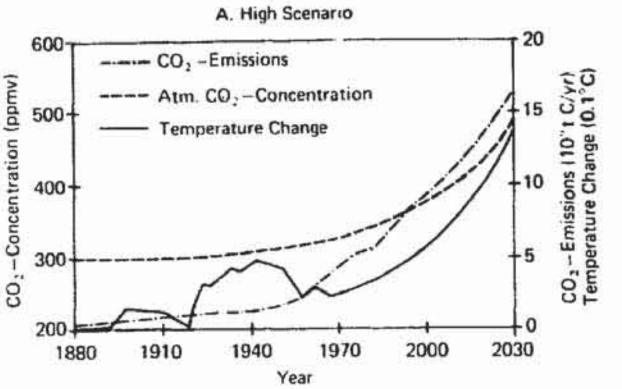

Fig. 10. CO_2 emissions, atmospheric CO_2 concentration and temperature change, high IIASA scenario [40].

2030 giving special attention to the different needs and possibilities of western industrialized countries, communist areas, developing countries and less developed countries.

Fig. 9 is a typical result of IIASA's world regional studies [40]. It illustrates how an increasing world oil demand is met, while oil supplied by the traditional producers, mainly of world region VI (ME = Middle East, NAf = North Africa) is kept constant. The complete scenario shows an interesting pattern for the supply mix in the world regions: coal and nuclear energy penetrates into the industrialized countries, while the oil consumption continues to grow rapidly in less developed countries. Another example of the IIASA scenario results is contained in Fig. 10, indicating the impact, which the energy consumption might induce on the climate in terms of temperature increases.

5. Unresolved issues and possible improvements in modeling

There are clearly various aspects related to the model development and application which are often subject to criticism. Several authorities, which are themselves involved in planning and policy assessment tend to suspect the 'new computer tools' offered. To put it more strongly, models are sometimes believed to be academic exercises with little practical value. This criticism may partly be moderated by the fact that modeling is a relatively new activity and that new methods of operations research have not generally penetrated into the process of decision making. Part of the problem also lies in the inflated expectations of what models can do. Because of this it is necessary to explore and define the boundaries on the application of models more precisely.

The modeler himself is probably never fully satisfied with his efforts and he is often in a position of being able to postulate a better system provided he could get the resources, the data and the interactions with planners.

This brings us to the first two points of possible future improvements:

(1) *Data gaps* are often replaced by 'soft numbers' and this merely mirrors the fact that an analytical investigation is only partly a matter of methodology. It is difficult to make a breakdown, but, as a rule of thumb based on experience, one might accept that 50 percent or more of the total manpower time effort for modeling should be dedicated to data assembly and analysis. Improvements are possible in both the allocation of efforts and the way input data are generated and brought into the models.

(2) *Communications* between analysts and planners are often quite understandably constrained by various time and manpower limits. But these hindrances very likely lead to what is sometimes expressed as 'the cultural gap' between the two groups. In fact, a better approach to the problems would be to work as a unified group with the planner involved in the analytical phase. This observation is supported by those modeling teams that have had to work in close liaison with energy planners.

The other two aspects concerning the modeling future are of a technical nature:

(3) *The integration* of the engineering/process analysis approach with the traditional econometric/behaviorial models has been exercised in various forms. It seems clear that complex questions of energy planning require methodologies of both disciplines to be available. But the synthesis of various techniques which deal with energy-economy interactions is still at an early stage of development.

(4) The *treatment of uncertainty* and variations of objectives is another subject deserving more focus and better analysis. It is probably one of the historical misunderstandings that many of the model results available today, are sometimes still believed to be forecasts. However, recognizing the uncertainty in many of the key parameters which

influence current decision-making, e.g. economic growth, oil (fuel) prices, consumer behavior etc. it must seem most unlikely for anyone to be a good forecaster. Instead, modeling may be used as a tool, to analyse futures under various assumptions, revealing insights to relationships which are non intuitive. This kind of approach may be helpful to determine 'robust' next steps for decisions. This particular area of model application certainly is one of the most promising but it requires future improvement in the techniques for computing sensitivity cases and for the stochastic treatment of variables.

Another area for improvement is partly covered by point 1, but is in itself an issue worthy of separate mention:

(5) The *geographical detail* that a model is able to picture is an essential measurement of its accuracy for planning. Improvements for regional modeling on county or city levels are desirable to encourage the application of models by planners.

Finally, the possible improvements can be concluded with a general statement on the art of documentation:

(6) *Documentation* of energy models and illustration of their application by representative case results are often not sufficiently comprehensive to reap the full benefits from modeling efforts. It is clearly a general issue how to present scientific results, but one of the guiding principles for such modeling work should be to provide others with the ability to reproduce and compare the findings. This is an area where modeling should invest in some specific improvements.

6. Conclusion

We have reviewed energy models and identified some areas of improvements for future modeling work. If those who are engaged in energy planning understand how to use these instruments and are able to encourage analysts, we would better know today what to do tomorrow!

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