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MODELING ENERGY-ECONOMY INTERACTIONS USING INTEGRATED MODELS

A literature survey

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Foreword

This report concerns an increasingly important issue, viz. the modelling of interactions between energy markets and economy. In the past suddenly rising oil prices were the driving force of this type of research, but presently the need for analysing scope and impacts of drastic CO_2 reduction measures stimulates this type of studies. We regret the delay in publishing this research conducted in 1992, but we find it interesting material for other researchers.

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1. INTRODUCTION

In this report the results are presented of a survey of integrated energy models. Integrated models are defined as economic energy models that consist of several submodels, either coupled by an interface module, or embedded in one large model. These models can be used for energy policy analysis.

Using integrated models yields the following benefits. They provide a framework in which energy-economy interactions can be better analyzed than in stand-alone models. Integrated models can represent both energy sector technological detail, as well as the behaviour of the market and the role of prices. Furthermore, the combination of modeling methodologies in one model can compensate weaknesses of one approach with strengths of another. These advantages motivated this survey of the class of integrated models.

The purpose of this literature survey therefore was to collect and to present information on integrated models. To carry out this task, several goals were identified. The first goal was to give an overview of what is reported on these models in general. The second one was to find and describe examples of such models. Other goals were to find out what kinds of models were used as component models, and to examine the linkage methodology. Solution methods and their convergence properties were also a subject of interest.

The report has the following structure. In chapter 2, a 'conceptual framework' is given. This is meant to give some historical background, to establish a uniform terminology, and to identify important aspects of model linkage.

In chapter 3 is proceeded by describing a number of integrated models. They have been chosen as examples of different methodologies. The terminology and classifications developed in the previous chapter are used. Surveys are given of the component models, the nature of the linkage, and the solution method. In a table, a complete overview is presented of all described models.

Finally, in chapter 4, the report is summarized, and conclusions are drawn regarding the advantages and drawbacks of integrated models. Some pitfalls for designers of integrated models are identified, and the importance of transparency is stressed.

The research has been carried out from February to April 1992 for Energy Research Foundation ECN.

2. CONCEPTUAL FRAMEWORK

2.1 The role of energy policy modeling

First, a number of potential roles of energy policy modeling are given. These are derived from Ahn (1985). These roles provide a general background for this paper because both applications of the models and a rationale of the use of integrated models are given. Some of these roles also apply to energy models in general.

These roles or uses are:
- They provide a *consistent framework* in which the interactions between the energy sector and the rest of the economy, among energy sub-sectors and among competing fuels and technologies can be studied in a coherent manner.
- They allow for timely 'what if' evaluations of many time pressing strategic and policy questions. So they can be used as a *strategic planning tool.*
- They provide a *common communication basis* for policy analysis. This is important in many situations where a particular policy action could cause conflicting interests among different groups.
- They serve as an educational or *learning tool.* According to Ahn, modeling creates experts, instead of experts creating models. The development process allows to gain insights and a better understanding of the energy sector.

Another way to look at integrated models is to consider the level of detail the component models incorporate. Ahn (1985) gives four different levels at which energy-economy interactions are generally modeled: macroeconomic growth, the interindustry composition of the economy, the interdependence of energy markets, and individual energy industries or markets.

Integrated models usually describe two or more of these levels which overlap in their economic content, but differ in their detail and in their way of organising supply and demand for energy (Ahn, 1985).

2.2 A bit of history

Some historical background will be given to the use of economic models in energy policy analysis. First, an overview of history concerning energy prices is given.

From 1950 to 1970, when there were no abrupt changes in energy prices, gross national product (GNP) growth rate was seen as one of the primary determinants of energy demand. In most energy models, the demand was taken exogenous (derived from the GNP growth rate) and the cost of energy supply was minimized.

In 1973, the Arab oil embargo caused a shock in the world economy, and energy prices rose dramatically. This caused fears for economic growth, because the industry had become very energy-intensive in the U.S. and Western Europe. The availability of cheap energy resources could no longer be taken for granted. Policy makers needed information on the interactions between the economy and what happened in the energy market. There was a demand for information about how relative product and factor prices, and the allocation of resources, might be affected by factors such as increasing energy costs, technological change in the energy sector, or various energy policy measures. Economic models were helpful because they gave appropriate quantitative projections, and sometimes combinations of models, describing different sectors in different detail, provided richer information than could be extracted from a single model.

The stable situation before 1970 has never returned. In 1979 a second oil price increase occurred, followed by an oil price collapse in 1986. This was caused by the decrease in energy demand in the eighties because of energy savings, and by intern disunity in the OPEC.

As a result of this situation, models that describe the interactions between the economy and the energy sector remain useful. The interest from policy makers varies somewhat with the political situation, however. Right now, a use of integrated models is to describe the economies in Eastern Europe, where both the economy and the energy sector are being restructured. Perhaps integrated models can capture and show some of the complicated interactions.

In the history of energy-economy modeling, four phases can be distinguished (based on Lakshmanan et al., 1985).

1. The first phase began around 1973, and was associated with the energy crises and higher prices. The historically similar growth rates of the economy and energy demand suggested a close relationship between the two. Hudson and Jorgenson were the first to analyze *the relation between economic growth and energy use in one integrated model* (using the model described in § 3.6). They identified a large substitution potential between energy inputs and other production factors. According to these results the scarcity of energy resources would not affect economic growth as seriously as was expected.
2. The second phase was the development of medium-term energy system models, a type of *model that treats the energy sector as an integrated system*. The Project Independence Evaluation System (PIES, § 3.1) and BESOM (§ 3.7) were among the first examples. PIES can handle a lot of detail in the energy sector, but also estimates the consequences of policies like import tariffs. These models were usually specified as linear programming models. A limitation of this class of models is that the economic determinants of the demand for useful energy, as well as the mutual interdependence of the energy sector and the rest of the economy are neglected.
3. This limitation induced the third phase; the development of *energy-economy models based on general equilibrium theory and the neoclassical theory of economic growth*. ETA-MACRO (§ 3.4) is an example.
4. The fourth phase is characterized by attention to environmental effects of energy technologies. The last few years, the greenhouse effect and other environmental problems have induced a growing concern for

conservation of energy and for limits on emission levels of energy technologies. So *energy-economy-environment interactions* were considered, or environmental assessment capability was added to existing models.

2.3 Terminology

In literature, several terms are used to designate integrated models. In this section, some definitions will be given in order to establish an uniform terminology throughout this report. Two classifications are used for this purpose, considering structure and scope of the models.

The general term, meaning all models consisting of multiple submodels, will be *integrated models.*

The first distinction to be made concerns the *structure* of the models:

- *Integrated models consisting of coupled submodels* are models in which the component models have remained separate, and have kept their original structure (possibly modified). The linkage is established by an iterative procedure. In literature, sometimes this is called a soft or indirect linkage.
- *Integrated models consisting of fully integrated submodels* are models in which the component models have been embedded in one common model framework. These models sometimes are called hardlinked or direct linked models.

In literature, many other terms can be encountered. Examples are combined, linked, coupled, hybrid, or integrated models, syntheses of models. The exact interpretation depends on the author. A confusing term is 'generalized equilibrium models'. These models belong to the class of integrated models consisting of coupled submodels. The terms submodels and component models are equivalent.

Another distinction considers the *scope* of the models:

- *Economy-wide integrated models.* These models give attention to interdependencies between energy markets and markets for labour, capital, materials, and final goods other than energy. This group of models is the most important subject of this survey.
- *Energy sector models.* These models describe the extraction of primary energy resources and the conversion and distribution of energy. They analyze specification of costs and capital requirements, energy products and their prices, and interfuel substitutions. They require a macrodriver or exogenous economic inputs since they do not include an explicit representation of the economy.

This distinction has an analogy in the difference between general and partial equilibrium models.

Finally, terminology needed for the description of integrated models is given (derived from Capros et al., 1989).

- A *link variable* is defined as being exogenous to one model and endogenous to another.

- *Interface modules*, which perform the transformation of link variables, establish the linkage.

2.4 Important aspects of model linkage

When integrating models, one has to consider many factors. Some of them have been described in literature. The information collected here gives an opportunity to identify some important aspects. Of course, a lot depends on the specific structure of the models that are to be integrated.

Boyd et al. (1990) identify an aspect of model linkage that holds for all kinds of component models: models must be collected under a *common set of assumptions*. Both the assumptions about the world and the data must be consistent. This is a basic requirement.

The following applies to integrated models consisting of coupled submodels. Capros et al. (1989) state that if some overlap exists between two submodels, then common endogenous variables should be made exogenous to one of the models, and corresponding equations should be eliminated from one model. Thus link variables are created. Next, interface modules must be created that perform the transitions of the link variables. These modules also serve to establish consistency between the different definitions, representations and aggregation schemes employed in the two models.

They also give a 'taxonomy of techniques for model linkage'. If the models that are to be integrated are dynamic, two cases can be distinguished:
- *intertemporal linkage*: the whole vector x_t, t=1...T, is transmitted from model 1 to model 2 and vice versa when performing a global iteration;
- *dynamic linkage*: the value of x_t for period t is transmitted from one model to another when performing a global iteration; when global convergence is achieved for period t results are transmitted to period t+1 and the convergence procedure restarts for the next period.

The convergence procedures largely depend on the solution method chosen and on the nature of the models, but in general two kinds can be distinguished:
- *empirical convergence*: established by the user who runs the models a number of times;
- *numerical convergence*: established automatically via a numerical algorithm (e.g. Gauss-Seidel) by using a severe convergence criterion.

Capros et al. indicate that the theoretical framework of general economic equilibrium is a useful framework for integrated models consisting of coupled submodels. Each submodel is expressing the optimizing behaviour of an economic agent, and the resolution algorithm implements the market clearing mechanisms for determining equilibrium prices. This allows the consistent linkage of models with different mathematical forms. Usually intertemporal linkage techniques are used. Hogan and Weyant (1983) describe the use of equilibrium theory as a framework for model linkage in more detail.

Hogan and Weyant (1983) also give a number of desirable criteria for integrated models consisting of coupled submodels:

- they should be based on a *consistent theory*;
- following the *natural organization of the data* to simplify the acquisition of these data and its application to the model structure;
- a *modular design*, so that individual components can be modified or expanded while the overall structure remains intact;
- they should allow *decentralized implementation of the submodels*, so that experts can focus on their own area of expertise; (many integrated models are developed from existing models, however)
- they should allow *efficient computation.*

Finally, a warning concerning integrated models *in general* is given by Donnelly (1987). He identifies the following drawbacks:

- the complexity of a model increases when techniques are combined, and the development of advanced integrated models requires large teams of modelers and large investments of time and resources;
- sometimes development of new solution methods is necessary;
- the costs of using combined models are much higher than the costs of using them separately;
- the resulting models are very large, so computational limitations can be a serious problem;
- the data requirements of an integrated model can be enormous.

So a good comparison of pros and cons should be made before undertaking such a project. Donnelly (1987, p. 28) warns that the purpose of the model should determine the approach: 'In practice, the modeling strategy sometimes dictates the questions to be addressed, which is a perverse approach to policy analysis. Much modeling might be categorized as a technique searching for a purpose.'

2.5 Summary

The oil crisis in 1973 gave rise to the development of models that describe the interactions between the economy and the energy sector. A special place in this class of models is taken by integrated models, which are better suited for this purpose.

The most important feature of integrated energy models is that they provide a consistent framework in which the interactions between the energy sector and the rest of the economy can be studied in a coherent manner.

Energy policy models in general (including integrated models) also can be used as a strategic planning tool or an educational tool, and they can facilitate communication.

Many different terms are currently used to describe integrated models. Throughout this paper, the term *economy-wide integrated models* is used for integrated models incorporating a macroeconomic model, and the term *energy sector models* is used for integrated models describing the energy system. Another distinction is made between *integrated models consisting of fully integrated submodels* where the component models have been embedded in one model, and *integrated models consisting of coupled submodels* where the component models have remained separate.

Concerning the integration of dynamic models, a distinction can be made between intertemporal and dynamic linkage. Also, two kinds of convergence procedures are distinguished: empirical versus numerical convergence.

It is desirable that integrated models consisting of coupled submodels should be based on a consistent theory, be modular in design, following the natural organization of the data, and suitable for efficient solution methods. Because both the costs of development and use of any integrated model are quite high, a careful comparison of pros and cons should be made. Moreover, the purpose of the model should determine the choice of a modeling approach.

3. DESCRIPTION OF SOME INTEGRATED MODELS

In this chapter, surveys will be given of eight different integrated models. These have been chosen as examples. The first two integrated models described are energy sector models, the others are economy-wide integrated models.

The models will all be described using the same framework. First the integrated model is introduced and some background is given, then the submodels are described separately. Next a description of the linkage or interface is provided, followed by information on the algorithm or solution method. The section 'additional information' can contain more about the methodology, applications and uses of the model. This depends on what was found in literature.

For a quick overview of the described models, the reader is referred to section 3.10. In this section a table is presented in which the most important features of the models are summarized. This table also can be used to select the most relevant model descriptions for a certain purpose.

3.1 Project Independence Evaluation System (PIES)

Introduction

Project Independence was initiated by president Nixon in March of 1974 after the Arab oil embargo, to evaluate U.S. energy problems and to provide a framework for developing a national energy policy. This energy policy was meant to establish U.S. independence of other countries for energy supplies by 1980.

The effort involved over 500 professionals, and resulted in an extensive series of reports. Among other outputs, there were predictions of the relationship among a number of key variables such as oil price, demand for oil and other fuels, possible government strategies, and gross national product. Later on, PIES was renamed the Midterm Energy Forecasting System (MEFS).

PIES is a static, medium-term energy sector model, that gives a partial equilibrium forecast of demand and supply of energy. A fundamental concept underlying the model is that prices will clear the market in all U.S. states.

PIES is an integrated model consisting of coupled submodels. These models are: an econometric demand model, a collection of supply models, and an 'integrating model'. The integrating model combines the outputs of other models to estimate market clearing prices and supplies and demands. Other models in PIES are the macroeconomic model that drives the demand model, and models for assessing equilibrium solutions. There is no feedback to these models and they will not be discussed here.

The models interface via data arrays, but are not connected in real time. In fact, the complete system employs several different languages and computersystems. The short time available for the project (± 7 months) made it necessary to use some existing models.

Description of submodels

The demand model is based on a separate econometric system of behavioral equations which relate the future demand for energy products to prices and other economic or demographic variables. It uses a macroeconomic forecast to establish the basic environment for the energy demand projections.

Output of the demand model (for each region):
- Initial demand estimates for fuel.
- Initial price estimates of fuel.
- Own and cross elasticities of the fuel types with respect to the price estimates of the 10 major fuel types.

The *demand model interface* prepares the demand data for use in the integrating model. Using the estimated demands, prices, and elasticities, it computes the matrix which is used in subsequent iterations to compute revised demands. Then it aggregates the demand and computes starting prices for the 8 final products.

The supply model component consists of a variety of procedures used to construct stepwise approximations for the energy supply curves. Incorporated are factors like technical knowledge, resource estimates, cost and profit calculations and judgement about the economic actions of the industry.

Output: tables of prices and associated quantities that are used in the integrating model to build the supply curve approximations.

Description of linkage

In PIES, the linkage is established by an 'integrating model', which combines outputs of the supply and demand models using an iterative procedure.

For a model of a competitive market, searching for a partial equilibrium, an equivalent optimization problem is to maximize the sum of producers' and consumers' surpluses, incorporated in a social welfare function. See Takayama and Judge (1971). By this property, the integrating model can have a linear programming structure while searching a partial equilibrium.

The integrating model combines the output from each of the other components, and solves for market clearing prices, supplies, and demands. Step-function approximations to resource supply curves are taken from the individual supply analyses, and are embedded within the linear programming structure of the integrating model. This cannot be done directly with the demand model, for there the demand for a particular fuel depends both on its own price, through own-price elasticities, and also on the price of competing fuels, through cross-price elasticities. Thus, at each iteration, the cross-price elasticities are neglected, but the own-price effects are incorporated through step-function approximations.

So the integrating model is a partial equilibrium model of the following type.

Supply side:

$$\min_{x} c^{T}x$$

$$\text{subject to}$$

$$\begin{aligned} & x \in X \\ & Ax = q \end{aligned}$$

Demand side:

$$q = Q_d(p)$$

Equilibrium condition:

$$p = \pi$$

where π is an optimal dual variable vector (shadow price vector) corresponding to the demand constraints $Ax=q$, c is a cost vector, X is the convex polyhedral production feasibility set which includes resource availability constraints and material balance constraints, and $Q_d(.)$ is a vector-valued demand function defined over prices, p.

Figure 3.1 gives an illustration of the interactions between the component models in PIES.

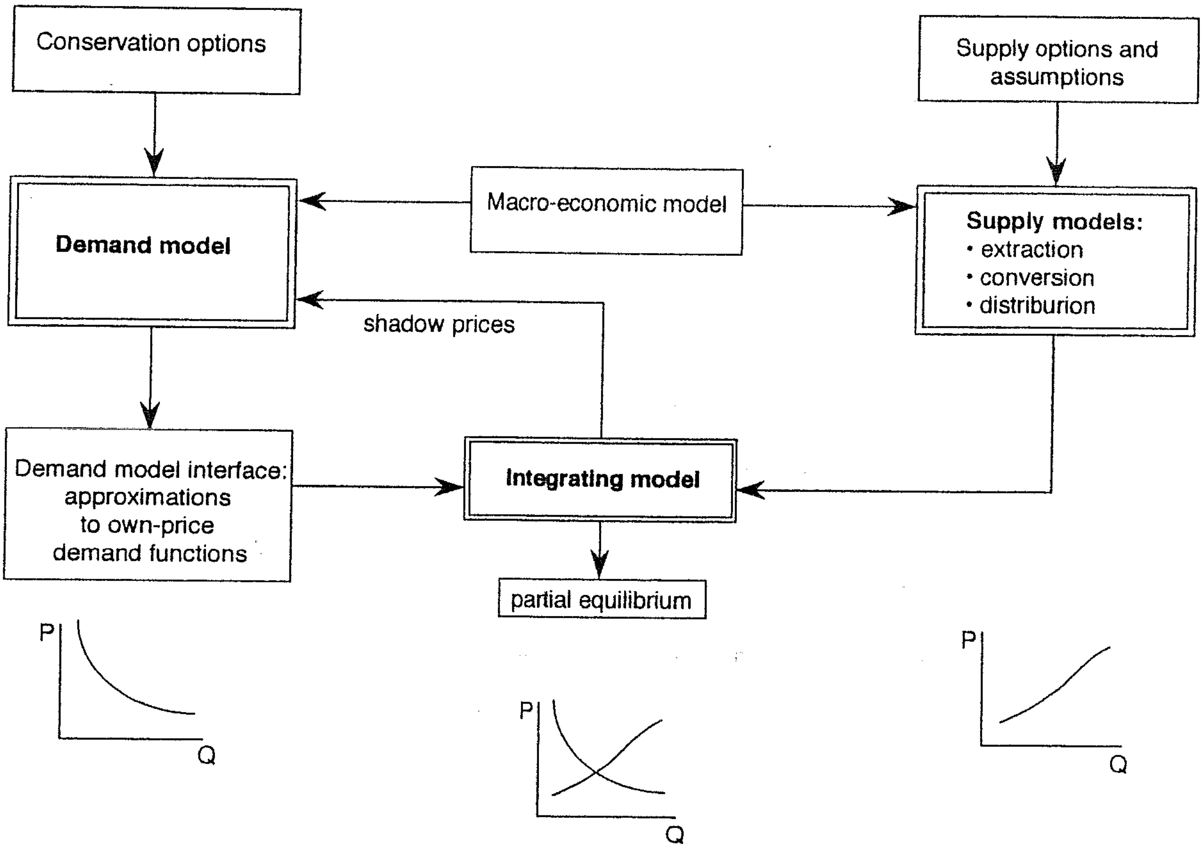


Figure 3.1 *The PIES model framework (based on Manne et al., 1979)*

Algorithm

Conventional optimization techniques cannot be applied directly to solve for an equilibrium, because of the cross-price elasticity terms. Instead, an iterative procedure is employed. At each iteration, the cross-price elasticities are neglected, but the own-price elasticities are incorporated through step-function approximations within the LP structure of the integrating model. At each optimal solution, there are shadow prices which serve as inputs to the econometric demand model for individual fuels. The econometric model produces a new set of own-price demand functions (again neglecting cross-price effects). These revised demand curves are incorporated within the integrating model, a new optimal solution is produced, and so on.

A short description of the algorithm:

- Step 1
  Choose a set of demand prices, P^1. Let t=1. *This is done by the demand model.*
- Step 2
  Calculate demand quantities $Q^t = Q(P^t)$. Using the own-price elasticities of Q(P) construct the stepwise approximation of the demand curve relative to the point (Q^t,P^t). *This is done by the demand model interface.*
- Step 3
  Obtain (x^t,Q^t,π^t) as an optimal solution for the LP model *(which is the integrating model)*, where x is the vector of activities in the energy system. If $\pi^t=P^t$, go to step 4. Else, let $P^{t+1}=\pi^t$, t=t+1 and go to step 2.
- Step 4

Terminate with equilibrium supply pattern x^t, consumptions Q^t and market prices P^t.

This interactive scheme is actually solving a fixed point problem. In Capros' terminology, this is a case of numerical convergence; established by the algorithm.

The possibilities for convergence depend on the integrability of the supply and demand functions. Ahn and Hogan (1982) give convergence criteria for models with a monotone supply mapping and linear or nonlinear demand functions. These convergence criteria are also sufficient conditions for existence and uniqueness of the market equilibrium. For the simplest case, with linear supply and demand relationships, they show that the algorithm is reduced to the classical method of Jacobi iteration for the solution of a large system of linear equations.

Hogan and Weyant (1983, p. 34) state that the specialized algorithm developed for Project Independence 'provided the first source of recognition of the power of the special computational procedures that develop and exploit approximations to the overall equilibrium problem'.

(Based on Ahn and Hogan, 1982; FEA, 1976; Hogan, 1975; Manne et al, 1979)

Additional information

Murphy (1983, p. 52) gives the following comments on MEFS (PIES): 'The strong points of MEFS are its completeness and modularity. Its weakest point is its lack of transparency. The human intervention between the satellite models and the integrating model gives the modeling an arcane flavour. [...] Yet, because of the large amount of attention to the individual sectors the model has a fair amount of realism, and it is the model with the most complete representation of energy programs designed to influence energy markets over the next ten to fifteen years.'

3.2 The SRI-Gulf energy model

Introduction

In the SRI-Gulf energy model, the names SRI and Gulf do not refer to component models, but to the Stanford Research Institute (*SRI*) which developed this model in 1973 to analyze synthetic fuels strategy for the *Gulf* Oil Corporation. Since then, it has been used widely in energy analyses by the U.S. government and other organizations.

The model is an energy sector model, describing the energy market in the United States in great detail. It is an integrated model consisting of coupled submodels, using the *'generalized equilibrium modeling'* methodology. This methodology is based on the idea of coordinated decomposition of complex decision problems. This idea involves breaking a complex model into a number of simpler submodels and then modeling the original decision problem by the coordinated use of the submodels. The basic elements of a generalized equilibrium model are:

- *processes* describing the fundamental submodels;
- *a network* describing the interactions among the processes;
- *an algorithm* for determining the numerical value of all of the variables in the model.

No single objective function is to be optimized in the model as it resembles decentralized market behaviour. The algorithm balances or satisfies all of the relations embedded in the processes. The resulting set of prices and quantities can be called the equilibrium solution, but it reflects whatever market imperfections and human behaviour are built into the processes.

Description of submodels

In the SRI-Gulf model the U.S. energy market is decomposed into about 2700 process models. A process is characterized by a set of mathematical relations. Each process can be defined as one of 7 basic processes. These are as follows:

1. *Simple conversion processes* describe the technology and economics of converting one energy material to another. So these processes are used in the model to describe representative energy technologies.
2. *Allocation processes* describe the allocation of demand among competing sources of supply. This is a simulation of the market decision making situation where buyers and sellers trade at a price. There are also allocation processes where the decisions are regulated by the government.
3. *Primary resource processes* describe the depletion and pricing of energy resources.
4. *End-use demand processes* describe the growth in demand for usable energy over time. Energy demand is a function of population, economic activity, and price (marginal cost) of energy services. It is possible to include more detailed representations of the economy and of feedback effects of energy on the economy in these processes.
5. *Transportation processes* describe technology and economics of moving an energy material from one location to another.
6. *Complex conversion processes* are conversion processes such as refineries or electric power generation.
7. *Secondary industry processes.* Secondary materials in the model are factors of energy production, conversion, and transportation. These processes describe the impact on secondary material prices of changes in demand for secondary materials used in construction of new energy facilities. They can be viewed as a simplified representation of the interaction of the energy system with the rest of the economy.

Each basic process has two types of relations. *Physical relations* describe the flow of materials within a process, while *behavioral relations* describe the decisions that determine prices and quantities.

The model has a dynamic structure. Thus within each of the process models installation and retirement of facilities over time is modeled.

Description of linkage

A network defines the links between the processes. The links are expressed as prices and quantities of energy products. The network has a hierarchical structure. At the top of the network are processes describing the end-use demands for energy, and at the bottom are processes describing primary resource supply. In between is a network of other processes describing market behaviour, conversion and transportation in the entire energy system. In figure 3.2 an illustration is given of the network structure.

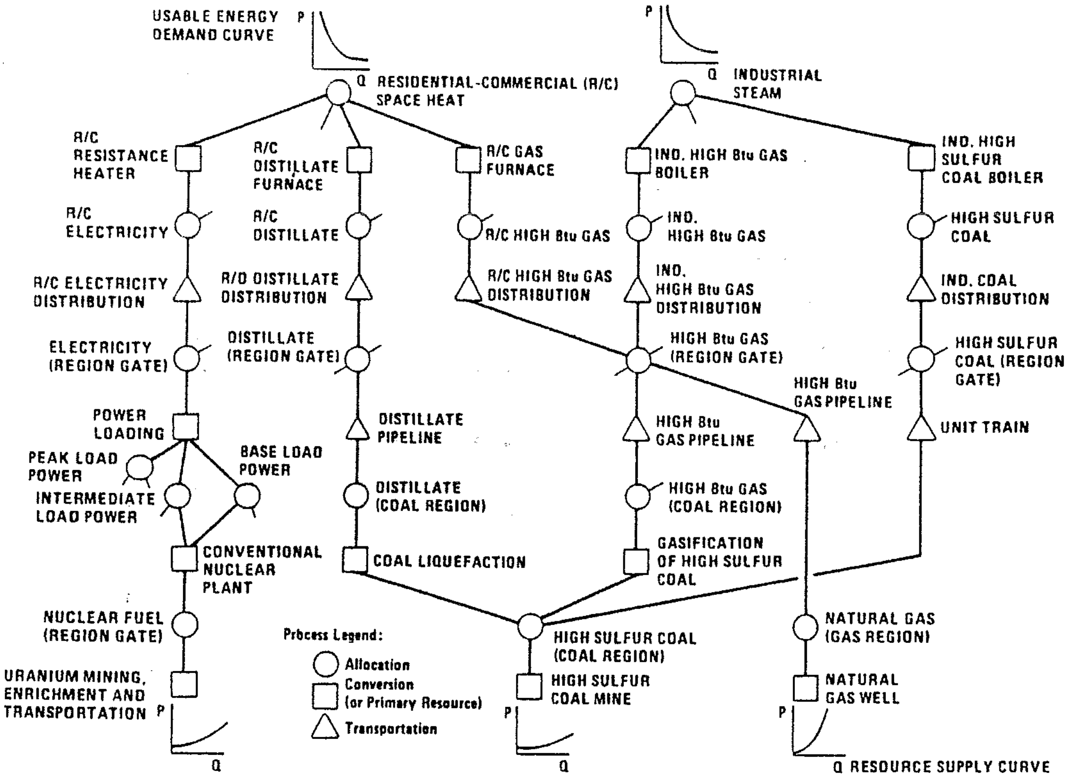


Figure 3.2 *Schematic diagram of the network structure of the SRI-Gulf model (Source: Cazalet, 1977, p. 2-3)*

Algorithm

The network algorithm is quite straightforward:

- Step 1

  (initialisation) Estimate q_t (quantity) for all outputs or inputs of processes.
- Step 2

  Compute p_t (price) for all outputs of processes working upward through the network and using the behavioral relations for each process. The computations for each process are performed backward in time.
- Step 3

  Compute q_t for all inputs to processes working downward through the network and using the physical relations for each process. Usually the computations for each process will be performed forward in time.
- Step 4

  Return to step 2 until all p_t and q_t are unchanged on successive iterations.

In iterating up and down the network, the prices or quantities of each process output or input are computed *for all time periods* before moving to the next output or input. So this linkage is intertemporal, in Capros' terminology.

The behaviour of the algorithm depends on the specific structure of the network. Convergence or divergence may occur, and that may happen slowly or in just a few iterations. It may oscillate back and forth among solutions while converging slowly, or diverging further from a solution. Therefore, modifications to the algorithm, called *relaxation methods* were developed. These methods interpolate among successive solutions of the algorithm in order to speed up the convergence. They are modified by experimentation. The number of iterations needed for convergence is most strongly affected by the character of the process relations and the associated input parameters.

The obtained solutions seem to be unique. Experiments using sensitivity analysis and different parameter sets gave no evidence of multiple solutions. It is possible to state uniqueness conditions by drawing on available uniqueness conditions for solutions of systems of nonlinear equations or for general economic equilibrium theory. But such conditions are of little practical value, while they are either very difficult to interpret, or very restrictive.

(Based on: Cazalet, 1977)

Additional information

The follow-up
In 1978, a few years after the development of the SRI-Gulf model, the Generalized Equilibrium Modeling System (GEMS) and the LEAP energy market model were built. The emphasis of LEAP is on long-term new technology analysis. GEMS provided the building blocks (the processes) used to construct the LEAP model. Nesbitt (1984, p. 1240) states that 'the GEMS/LEAP approach is significantly more advanced in its representation of producer and consumer behaviour, its representation of market dynamics, its solution algorithm, and its relationship to accepted economic and mathematical programming theory' than SRI-Gulf.

According to Murphy (1983), a mistake built into LEAP is that the oil price is determined incorrectly. But correcting this mistake deviates from the generic nature of the GEMS software and models, because there is one general pricing rule for all energy products, including oil. This inflexibility can be seen as a drawback of this structured way of modeling.

Murphy also gives a critical remark on the transparency of LEAP (p. 55): 'The nodes are essentially reduced form models; there is no structural representation of actual decisions. At the same time it lacks the simplicity of a truly reduced form model with few equations. This structure makes the results harder to explain.'

3.3 The integration of ELIAS and ENMARK

Introduction

After the description of two energy sector models, this is the first economy-wide integrated model surveyed.

In 1985, Lundgren established an integration between an activity analysis model of the energy sector (ENMARK), and an applied general equilibrium model (ELIAS), which yielded an integrated model consisting of fully integrated submodels. The two models were integrated using the optimization framework. This was motivated by the fact that a computational approach was necessary which could handle weak inequalities and complementary slackness (from the equilibrium model). From the possible solution methods, the optimization approach seemed the most promising.

Description of submodels

ELIAS

The ELIAS (Energy, Labour, Investment; Allocation and Substitution) model is a computable general equilibrium model. It is especially designed for analysis of problems related to national energy policies in an small open economy, which is Sweden in this case. Two energy categories, electricity and fuels, are explicitly distinguished and while all other intermediate goods input coefficients are exogenous, the energy input coefficients are determined endogenously. The household demand for energy is specified per sector of electricity or fuel producing industries.

ELIAS is a medium term model characterized by sector specific capital stocks. Although the model can be used to simulate a development over time for the model economy, it is not an intertemporal model, but a one period model. The dynamics are simulated by a sequence of one period equilibria, which are linked by investments that yield a new set of vintage capital stocks. Given these, and with all exogenous variables updated, a new period equilibrium is established.

ELIAS incorporates one aggregated household sector. Foreign trade is modeled using the Armington assumption.

ENMARK

The electricity and heat supply model ENMARK (ENergy MARKets model) is a medium term activity analysis model which describes four energy markets at a given time period. These four markets are the nation (=Sweden)-wide electricity market and three regional markets for heating energy.

ENMARK is a partial equilibrium model, but mathematically it is designed as an optimization model. Thus, the sum of producers' and consumers' surpluses is maximized or the cost of satisfying demand is minimized. By an equivalence theorem, the solution then can be interpreted as a competitive (partial) equilibrium.

The demand side of the model is exogenous. The demands for electricity and heat can be satisfied in several ways by different combinations of production technologies. There is also a set of investment activities by which the initial capacities of the different production technologies are augmented. Utilization of these activities and technologies is associated with a cost.

There are two types of linear constraints. Market equilibrium constraints require that the supply be at least as large as the corresponding demand. Capacity constraints require that total production does not exceed the initial capacity plus capacity additions.

Description of linkage

The two models are directly integrated into one optimization model. Using results from welfare economics, the general equilibrium model ELIAS is formulated as a (Pareto-type) nonlinear programming problem. Lundgren (1985) proves that under certain conditions, taxes can be included while still an optimization formulation is possible. This feature is used when the ENMARK objective function is incorporated in the ELIAS objective function.

In the integrated model, ELIAS and ENMARK were modified as little as possible, so the results of the integrated model could be compared to output of the separate models.

The integrated model is created by replacing the electricity and heat sector production constraints in ELIAS with the ENMARK model. Because the ENMARK supply part is not completely comparable to the corresponding sector in ELIAS, the commodities in ENMARK must first be related to those in ELIAS.

Linking the final outputs of ENMARK to the demand in ELIAS involves the following steps:

- The demand for one aggregated energy commodity in ELIAS is disaggregated to the electricity and heat demands in ENMARK, using exogenous (sector-specific) parameters that represent the sector's use of electricity and heat, and convert the demand from constant prices into physical units.
- The intermediate heat demand in ENMARK is determined in the same way, except for a modification in the residential sector, where only a part of the ELIAS demand is for heating.
- Export and import variables for electricity in ELIAS are replaced by export and import activities for electricity from ENMARK.
- The distinction between electricity for heating and for non-heating purposes is accounted for. For each ELIAS production sector is assumed that a certain proportion of its electricity demand is for heating purposes.

Linking the inputs required in ENMARK's production activities to the final outputs in ELIAS involves the steps:

- The use of oil in the ENMARK part is linked to the petroleum producing sector in ELIAS. Uranium and coal are not domestically produced, but are treated as complementary imports to the electricity and heat sector.
- The domestically available solid fuels (wood chips, peat and waste) incorporated in ENMARK, are linked to the more aggregated final outputs in ELIAS by a disaggregation rule.
- Since the ENMARK model only contains energy and capital costs whereas in the corresponding ELIAS part costs of non-energy intermediate inputs and labour use also are incorporated, these are in the linkage added in fixed proportions to the production activities for electricity and heat.

- In some production activities in ENMARK distribution costs are included. These costs are treated as taxes in the integrated model. They affect production and investment decisions but do not correspond to actual resource requirements.

The *objective function* in the integrated model is essentially the same as in ELIAS, but it also incorporates the linear cost term associated with the ENMARK production activities. This term is formulated as taxes which are imposed directly on the activity levels.

The *constraints* in the integrated model are production technology constraints and market equilibrium constraints.

The production technology constraints can be subdivided into two groups:
- the ELIAS constraints which now apply to the ENMARK model instead of the ELIAS electricity and heat sector;
- constraints giving the production technologies in ENMARK. These are summarized by the matrix B. One subset of the rows of B represents capacity constraints, another subset represents any other type of connections between different activities which the model contains. The remaining part of the matrix B are rows corresponding to commodities which are exchanged between the two models.

The market equilibrium constraints are the following:
- the ELIAS market equilibrium constraints, except that the intermediate demand from the electricity and heat sector is replaced by ENMARK activity input requirements;
- the market equilibrium constraint for the ELIAS heat and electricity sector is replaced by several market equilibrium constraints describing electricity and heating energy for the different local heat markets;
- the current account constraint is extended with a set of trade variables related to the ENMARK model.

The models have different treatments of investments. In the integrated model, first the investments in the energy sector are determined, then the rest of the exogenous investments are allocated using the ELIAS allocation equations.

Algorithm

ELIAS-ENMARK can be solved by a general purpose optimization algorithm. Lundgren gives no information on which specific solver was used.

Additional information

The integrated model was used to look at two issues concerning the role of nuclear power on the Swedish electricity market.

In Sweden a nuclear power discontinuation policy is being adopted. The consequences of this policy were assessed by comparing the development of the model economy in two different main simulations. The results indicated that the electricity price would increase and the demand for electricity would decrease. The effects on GNP growth would not be dramatic.

The large nuclear power investment programme in Sweden was evaluated by comparing it to one in which nuclear power investments only occur if the electricity price is sufficiently high to cover the long run marginal cost of nuclear power. The simulations then indicate that between 1980 and 1985, a large part of the nuclear power capacity that was added was 'economically dubious', and caused excess capacity.

3.4 ETA-MACRO

Introduction

ETA-MACRO is a dynamic general equilibrium model of the U.S. economy. It is an integrated model consisting of fully integrated submodels. The submodels are an aggregated one-sector growth model and a detailed process model of the energy sector. The integrated model is formulated as a non-linear program, but using results from welfare economics, the solutions to the model can be interpreted as equilibria in a competitive economy.

The model describes the relation between economic growth and the energy system. The focus is on long-run issues of energy-economy interactions, resource extraction, and new technologies. Energy-economy interactions occur in two ways. The output of the economy is used to pay for energy, and energy is an input to the economy.

The base year is 1975, and the projections cover five-year intervals from 1975 to 2050. There is only one economy-wide production function, so the economy is described in highly aggregative terms. Within the energy sector, only two categories are distinguished: electric and nonelectric energy. There is one single representative producer and consumer. Taxes or subsidies are not incorporated.

Description of submodels

ETA

The Energy Technology Assessment model is a partial equilibrium model covering the U.S. energy sector, that is formulated as a nonlinear programming model. It determines:
- levels of production and conversion of energy,
- demand for electric and nonelectric energy,
- quantities of fuel resources required,
- energy sector costs.

It incorporates both own- and crossprice elasticities for electric and nonelectric energy. ETA includes constraints on:

> *capacity, demand, natural resource requirements, uranium enrichment requirements, availability of natural resources, cumulative resource requirements, cumulative plutonium stockpile, annual investment rates, coal limits, and energy costs.*

The objective is maximizing the sum of consumer's and producer's surpluses.

MACRO

MACRO is a neo-classical macroeconomic growth model (sometimes referred to as a general equilibrium model), formulated as an optimization model. The pattern of investment and consumption over successive time periods is maximized using a logarithmic utility function.

It incorporates one production function for the whole economy, which provides for substitution between capital, labour, and energy inputs. The model includes the following equations:

- Output is allocated between interindustry payments for energy costs, consumption and investment.
- The economy-wide production function. Gross output depends on four inputs: capital, labour, electric and nonelectric energy. The production function has a nested nonlinear form.
- Equations that describe capital accumulation. Within each period, net new capital formation is determined by gross investment less depreciation.

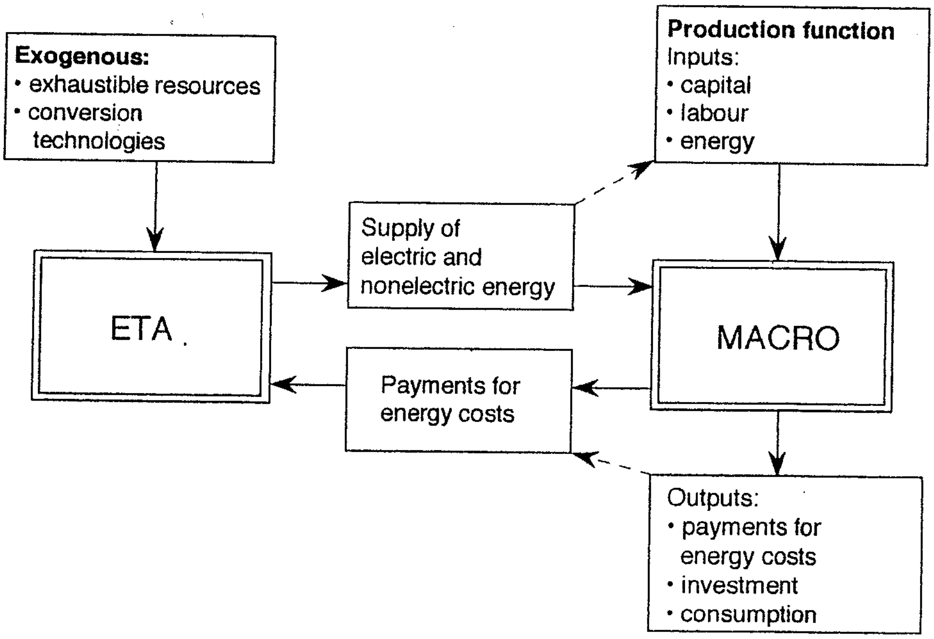


Figure 3.3 *Economic flows in ETA-MACRO (based on Manne, 1977)*

Description of linkage

Not much information is given on the nature of the linkage. But it is clear that the linkage methodology is similar to the methodology used by Lundgren when integrating ELIAS and ENMARK. ETA-MACRO also is fully integrated, and should be viewed as one (nonlinear optimization) model. The MACRO utility function is taken as maximand, subject to both ETA and MACRO constraints. The ETA objective function is incorporated in one of the constraints.

In figure 3.3 is shown that interactions between ETA and MACRO occur in two ways. The output of the economy is used to pay for energy, and energy is an input to the economy. But the scheme is misleading in that it suggests that the two models have remained separate.

Interesting is that Ahn and Seong (1983) give the mathematical formulation of a dynamic nonlinear optimization model 'similar to ETA-MACRO'. Next they decompose this model, so they work in the reversed direction. These formulations give an idea of the structure of ETA-MACRO:

$$\max \sum_{t=1}^{T} U(Cs_t)/(1+r)^{t-1}$$

subject to

$$f(K_t,\bar{L}_t,E_t,N_t)-Cs_t-(K_{t+1}-K_t)-c_t x_t=0 \quad (t=1,..,T) \tag{1}$$

$$\sum_{t=1}^{T} A_t x_t=b$$

$$A_{E_t} x_t-E_t=0 \quad (t=1,...,T)$$

$$A_{N_t} x_t-N_t=0 \quad (t=1,...,T)$$

$$x_t \geq 0$$

Where:

$\bar{L}_t$: exogenously given (overbarred) labour force level (in efficiency units);
K_t: capital stock level at the beginning of time t (where K_1 is given exogenously as an initial condition);
E_t: electric energy demand/supply quantity;
N_t: nonelectric energy demand/supply quantity;
Cs_t: consumption level;
x_t: linear activity vector for energy technologies;
c_t: cost vector for energy technology operation;
A_t: coefficients relating activities of different time periods (capacity expansion, cumulative resource restriction and other system constraints);
A_{Et}: coefficients for demand requirements of electric energy;
A_{Nt}: coefficients for demand requirements of nonelectric energy;
all at time t;
b: vector of system constraints;
r: annual utility discount rate;
U(.): national utility function;
f(.): nonenergy sector production function.

Ahn and Seong then decompose problem (1) into a nonenergy sector component (2) and an energy sector component (3), using Kuhn-Tucker conditions. The nonenergy sector submodel resembles MACRO in that it uses one economy-wide production function:

$$\max \sum_{t=1}^{T} U(Cs_t)/(1+r)^{t-1}$$

$$\text{subject to} \qquad (2)$$

$$f(K_t,\overline{L_t},\overline{E_t},\overline{N_t})-Cs_t-(K_{t+1}-K_t)-c_t\overline{x_t}=0 \qquad (t=1,..,\mathrm{T})$$

In this nonenergy sector problem E_t, N_t, and x_t are exogenously given from the energy sector submodel, which probably resembles ETA:

$$\min \sum_{t=1}^{T} \overline{\mu_t} c_t x_t$$

$$\text{subject to}$$

$$\begin{aligned}
&\sum_{t=1}^{T} A_t x_t = b && (3)\\
&A_{E_t} x_t - E_t = 0 \quad (t=1,...,\mathrm{T})\\
&A_{N_t} x_t - N_t = 0 \quad (t=1,...,\mathrm{T})\\
&x_t \geq 0
\end{aligned}$$

In this energy sector submodel μ_t is exogenously given from the nonenergy sector submodel, where μ_t is the shadow price. So the link variables are E_t, N_t, x_t, and μ_t.

Algorithm

The nonlinear programming model can be solved by MINOS, which utilizes reduced gradient optimization.

(Sources: Manne, 1977; Bergman, 1988)

Additional information

ETA-MACRO was first developed by A.S. Manne in 1977. In 1990, the model was used in 'Global 2100', an analytical framework for estimating the costs of a CO_2 emissions limit. In Global 2100, parallel computations are done for the world divided in five regions. Within each region, the analysis is based on ETA-MACRO

(Manne and Richels, 1990)

Another recent project was the linkage of MARKAL -a nonlinear programming energy sector model- and MACRO. This linkage is based on the same ideas as ETA-MACRO. A short description of this linkage can be found in section 3.9.

3.5 The HERMES-MIDAS linked system of models

Introduction

The HERMES-MIDAS linked system of models differs from the other integrated models described here in the 'macro-economic paradigm' adopted. The macro-economic model HERMES is based on neo-Keynesian economic theory. As a result the model represents a demand-driven economy. HERMES-MIDAS is an integrated model consisting of fully integrated submodels. Roughly, the linkage is established by replacing the energy demand equation of HERMES with the energy demand model MIDAS.

The project of linking these models was promoted by the Commission of the European Communities. HERMES and MIDAS were chosen for the linkage because they are available for all European countries. The final aim of the project is to provide a complete model system for European-wide medium-term energy policy analysis and to assist the quantitative analysis of the complex energy-economy interactions.

Description of submodels

HERMES

HERMES (Harmonized European Research for a Multinational Economic and Energy System) is a large-scale macro-economic model giving emphasis to energy. The model has the form of a system of nonlinear equations. Energy is represented in three roles. Energy as a production factor is included in the production function, energy as an industry is represented by adding a producing sector, which incorporates production and conversion activities as well as labour and capital in the energy branch, and energy imports. Energy as consumption commodity is represented by a system which allocates consumption between energy and nonenergy goods.

MIDAS

The Multinational Integrated Demand And Supply model (MIDAS) has two components.

MIDAS-Demand is an econometric model. Final energy demand is evaluated as a function of macroeconomic variables such as sectoral production, income and inflation, and energy prices.

MIDAS-Supply-Prices is a large-scale simulation model of energy supply and prices. The energy conversion system is considered in detail. Included are modules on electricity production, refining, coal production, natural gas production, coke and synthetic gas production, and energy prices.

The supply model matches energy demand and supply. Production and conversion costs determine domestic energy prices. These are then reintroduced in the demand model. Because the prices are determined by a markup process on costs, an oligopolistic market structure is modeled instead of perfect competition. Energy is measured in physical units.

Description of linkage

HERMES-MIDAS is an integrated model consisting of fully integrated submodels. The main linkage procedure is as follows. Both models are modified by eliminating energy equations from HERMES and macroeconomic equations from MIDAS. Then they are linked by interface modules performing transformations of link variables. As illustrated in figure 3.4, the interface between the modified models is organized in two modules which perform transitions of three types of variables:

- *common exogenous*, such as oil price, population, interest rate and exchange rate, which should be the same in both models;
- *endogenous in HERMES and exogenous in MIDAS*, such as GDP, wage rate, rate of inflation;
- *endogenous in MIDAS and exogenous in HERMES*, such as energy demand, supply and prices.

The transformation of endogenous variables of HERMES into adequate input for MIDAS (and vice versa) caused serious problems, because of different levels of aggregation and of different statistical schemes of the two models. Mathematically, the HERMES-MIDAS linked system can be considered a single model, composed of about 1500 simultaneous equations.

A study was conducted to define the implications of replacing the energy demand equation of HERMES with the energy demand model MIDAS. The conclusions drawn were that the alteration of the behaviour of the model(s) was not 'qualitatively significant' if:

- the MIDAS energy demand equations shared some common properties with the equations eliminated from HERMES;
- MIDAS demand elasticities were within a range depending on the respective elasticities of the original HERMES model.

So all differences in the properties of the stand-alone HERMES and the linked system are of a limited quantitative nature, without significant qualitative discrepancies.

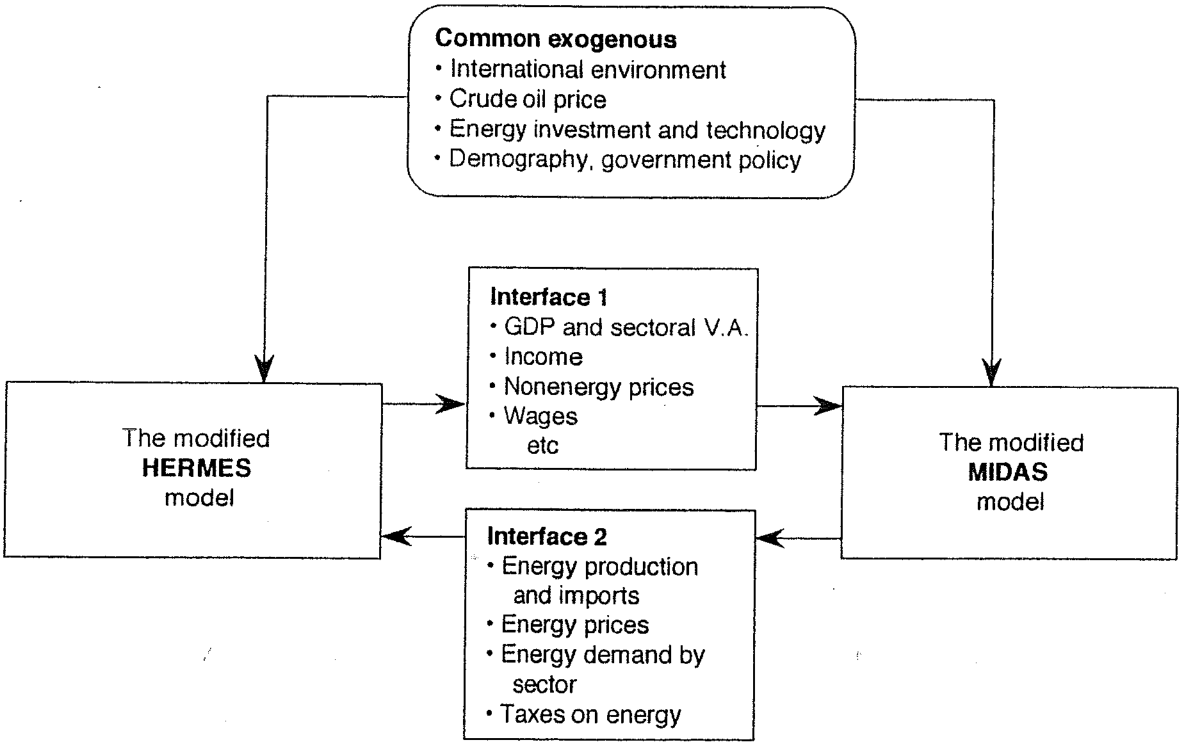


Figure 3.4 *Interactions within the HERMES-MIDAS linked system (based on Capros et al., 1989)*

Algorithm

A numerical convergence procedure was implemented. The whole system is composed of about 2500 simultaneous equations and is running in the TROLL environment. The linkage is dynamic. More detailed information was not available on the algorithm.

Additional information

An analysis of HERMES-MIDAS linkage properties was carried out with a number of simulation exercises dealing with energy and economic variables. This was done by injecting exogenous shocks into both the original HERMES model and the linked system. The results were compared. A final conclusion was that the HERMES-MIDAS model appears to be a more consistent and comprehensive tool for energy-economy analysis, especially for the study of energy and energy related shocks.

However, if macroeconomic analysis is performed and energy impacts are not of primary interest, the original HERMES model is quite accurate.

(Based on Capros et al, 1989)

3.6 The Long-term Interindustry Transactions Model

Introduction

The Long-term Interindustry Transactions Model (LITM) is designed to provide a framework for analyzing the effects of economic changes on the energy system and the effects of energy changes on the structure and growth of the U.S. economy. The original model was designed by Hudson and Jorgenson, later versions of the model were called the DJA (Dale Jorgenson Associates) model. It was a pioneering effort to incorporate energy sector detail in an econometric model.

LITM is a dynamic model of the structure and growth of the U.S. economy. It can be considered an integrated model consisting of fully integrated submodels. The submodels are a macroeconomic and an interindustry model.

The model determines the price and distribution of each type of energy and the price and distribution of nonenergy products through the equilibration of supply and demand. The prices are determined in such a way that supply and demand are equal for each product.

The model uses two innovations that provide flexibility in modeling production. These are:
- the use of production functions based on the translog form, a mathematical structure of great generality;
- a production structure with endogenous input-output coefficients, based on the prices of output and of primary and intermediate input.

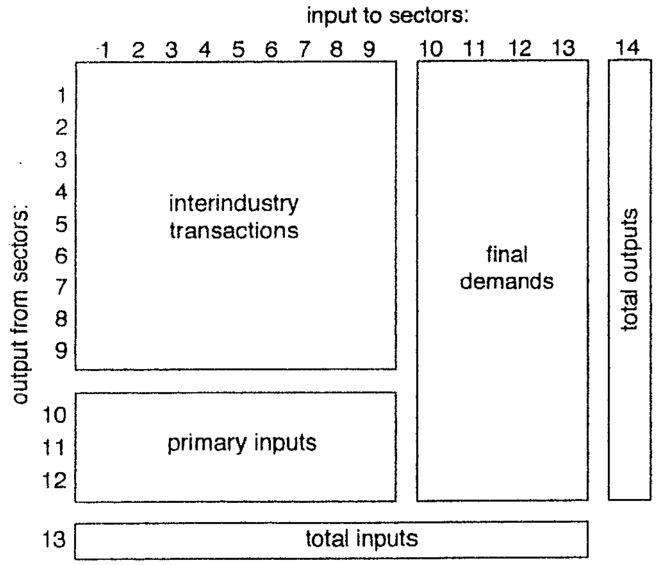
Sometimes this model is referred to as being a 'Walrasian' dynamic general equilibrium model of the economy (i.e. Groncki, 1978).

Description of submodels

Interindustry submodel (LITM supply-side)
The interindustry model consists of an input-output-model and econometric models of producer behaviour for each of the sectors. The model divides the private domestic sector of the economy into nine industry groups, including five groups within the energy sector. For each of the sectors, the model determines:
- the equilibrium quantity of output
- the equilibrium price of output;
- the quantities of input used in the production processes, including intermediate goods supplied by all nine sectors, capital, labour, and imports.

There are three categories of primary inputs -capital services, labour services, and imports- and four categories of final demand -consumption, investment, government purchase, and exports. More details are given in figure 3.5.

The econometric models of producer behaviour for each sector derive the input-output coefficients that are used in the input-output-model. They are based on the production functions for each sector. The production functions are not estimated directly, but based on the price possibility frontier.



industry sectors:
(nonenergy sectors)
1. agricultural, nonfuel mining and construction
2. manufacturing, excluding petroleum refining
3. transportation
4. communications, trade, and services
(energy sectors)
5. coal mining
6. crude petroleum and natural gas
7. petroleum refining
8. electric utilities
9. gas utilities
primary inputs:
10. imports
11. capital services
12. labor services
final demands:
10. personal consumption expenditures
11. gross private domestic investments
12. government purchases of goods and services
13. exports

Figure 3.5 *The interindustry structure in LITM (based on Groncki and Marcuse, 1979)*

Macroeconomic submodel (LITM demand-side)
This model of U.S. economic growth provides:
- totals for the four categories of final demand in the econometric model of interindustry transactions;
- the relative prices of capital and labour, which enter as primary inputs into the nine sectors of the interindustry model.

Hudson and Jorgenson state that their approach to the explanation of economic growth is ‘closely related to the neoclassical theory of economic growth’. They assume economic growth results from the link between current capital formation and future production capacity. In the model this link is provided by a macro-econometric production function, relating the output of consumption and investment goods to the input of capital and labour services.

The macroeconomic model integrates demand and supply conditions for consumption, investment, capital, and labour. Exogenous to the model are the behaviour of the foreign and government sectors and demographic trends.

This model also includes a model of consumer behaviour that allocates personal consumption expenditures among the commodity groups included in final demand. The quantities purchased as functions of total expenditure and the prices can be generated from an indirect utility function, giving the maximum level of utility attainable for given total expenditure and given prices. This maximum level of utility depends on the substitutability of alternative goods and services in consumption. Figure 3.6 gives some insight in the interactions between the submodels.

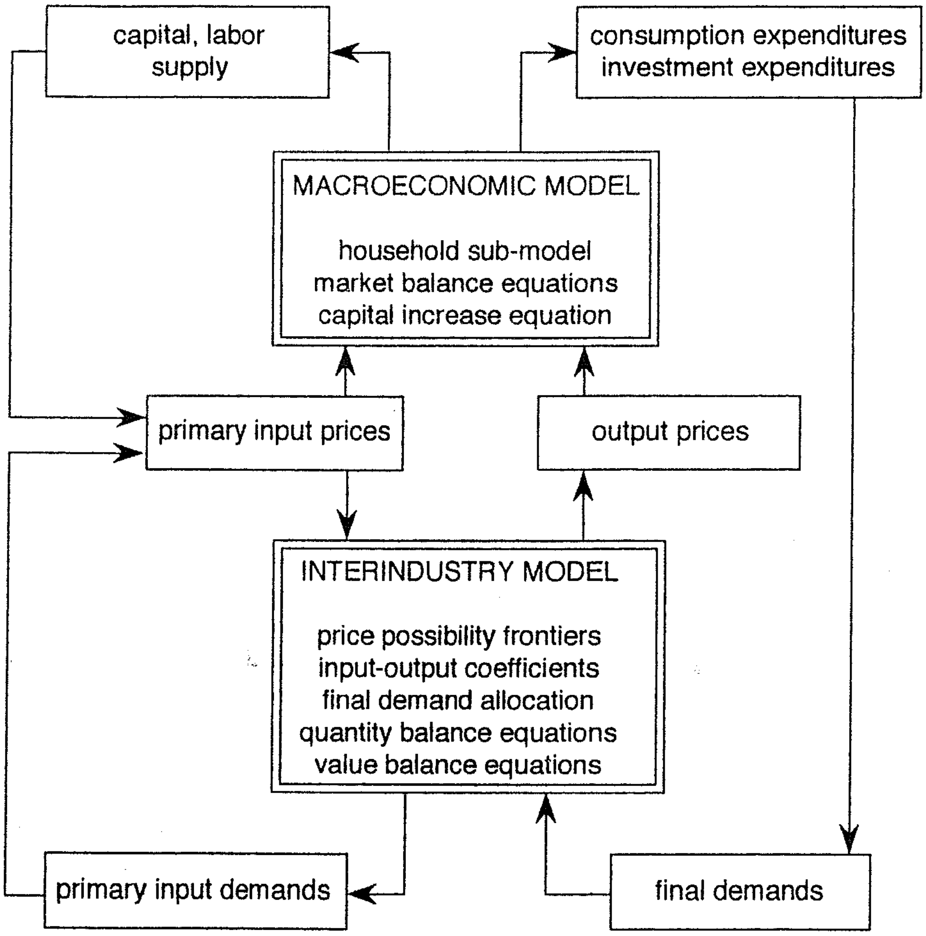


Figure 3.6 *The structure of LITM (source: figure 2, Hoffman and Jorgenson, 1977)*

Description of linkage

The different components make up one econometric model. Mathematically, it is formulated as a system of simultaneous equations.

Algorithm

Bernanke and Jorgenson (1975) give the following information on the solution procedure. The LITM model requires solutions of simultaneous equations systems in several places- for the simultaneous solution of the price possibility frontiers and the solution of the input-output system, among others. No external source or package is called for this purpose; instead, the program contains its own algorithm, based on Newton's method.

(Based on Bernanke and Jorgenson, 1975; Groncki and Marcuse, 1979; Hoffman and Jorgenson, 1977, Hudson and Jorgenson, 1974)

3.7 LITM linked to an optimization model

Introduction

LITM-BESOM can be considered an integrated model consisting of coupled submodels.

Hogan and Weyant (1983, p. 35) make the following remark on this model: 'One of the most successful examples of the integration of an energy model with a model of the complete economy is found in the work of Hudson-Jorgenson, in cooperation with Brookhaven National Laboratories. Here we see one model, dominated by the methodology and techniques of econometrics, used to describe the bulk of the economy, and then linked with a linear programming model of the energy sector defined through the careful engineering analysis of energy technologists.'

So it cannot be missed in this survey because of its 'historical value'.

Description of submodels

BESOM

The Brookhaven Energy System Optimization Model (BESOM) is based on the allocation of energy supplies to energy demands to minimize cost of meeting end-use energy demands from resource extraction through conversion, distribution, and end use. The minimization of cost is formulated as a linear programming problem of the transportation type, with sources identified with energy supplies, and uses identified with energy demands. BESOM is a static, single year model and considers interfuel substitution.

Exogenous to the model are:
- the level of demand for energy services;
- annual production constraints on supply of energy resources;
- availability constraints on new technologies;
- characterization of technologies in terms of conversion efficiency, capital, operating cost, and emissions to the environment;
- definition of any special constraints required to reflect policies or market forces that result in departures from an unconstrained optimum.

Given these data, the optimization determines:
- a set of energy conversion levels that minimizes the cost of satisfying energy product demands from energy resource supplies.

The dual to this linear programming problem is to maximize the value of energy products less the value of primary energy supplies by choosing a set of energy product and energy resource shadow prices. These shadow prices assure that the value of the output of each conversion process in actual use is equal to the value of input, including the input cost of primary energy supplies and any scarcity shadow prices and costs of extraction, conversion, and transportation.

Activity levels are given in terms of the quantity of fuel or energy delivered from a supply trajectory to end use.

The LITM model has been described in the previous paragraph.

Description of linkage

The two models are indirectly integrated through modifications on LITM and an iterative solution procedure. The two models then form *the integrated model.* An outline of the integrated model is given in figure 3.7.

The integrated model is based on an expanded version of the interindustry model that is a part of LITM. The energy sector (originally consisting of five energy producing industries) is now divided into three categories of transactions, involving energy resource sectors, energy conversion processes, and energy product sectors. The remaining components of the interindustry model -interindustry transactions in nonenergy products, primary inputs and final demands- are also included in the expanded version.

The integrated model incorporates:
- balance equations between supply and demand for products of each of the 51 sectors included in the expanded model;
- technical coefficients for the energy sector from BESOM;
- technical coefficients for the nonenergy sector from the production models from LITM;
- final demands for energy and nonenergy products from LITM, allocated among the energy products of BESOM.

In the integrated model energy flows are given in Btu's (British thermal units), while nonenergy flows are measured in dollars.

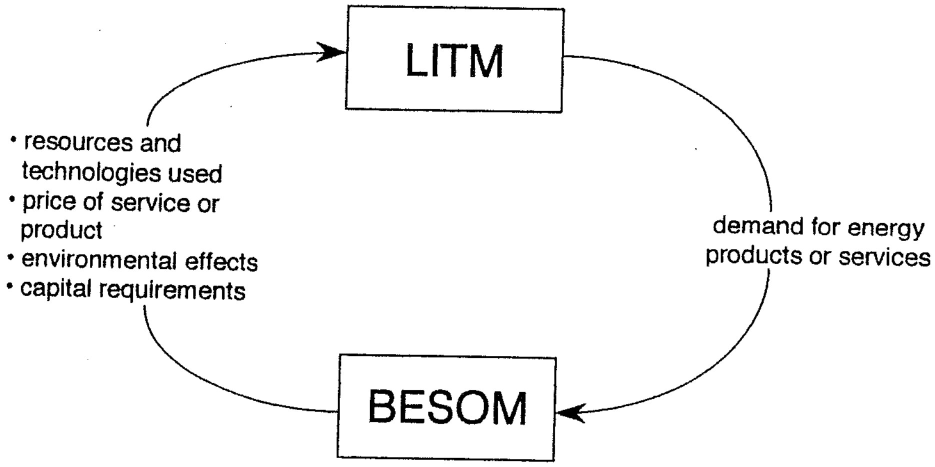


Figure 3.7 *Combined econometric and process analysis model (figure 1, Hoffman and Jorgenson, 1977)*

Hoffman and Jorgenson (1977) do not explain what the purpose and use is of the expanded version of LITM. Whenever the integrated model is spoken of, it includes the expanded LITM. But in the algorithm, the original version of LITM (together with BESOM) is used to update variables in the integrated model. It can be concluded that this linkage is a *very indirect* and not very transparent one. Two versions of the same model are used simultaneously.

Another strange feature is the treatment of time. A linkage is established between a dynamic and a static model, without the authors ever mentioning the treatment of time. A hypothesis is that static versions have been used of both LITM and BESOM, and that development over time is simulated by a series of solutions.

Algorithm

The integrated model is solved in three steps. These steps are repeated until the data employed to initiate the process (which are the solution of the previous iteration) are generated as a solution of the integrated model.

- Step 1

  Solve LITM (original version) and BESOM separately, using data from the previous iteration.

  Using the solution to LITM determine:

  a. Final demands for the nonenergy industrial sectors, and demands for 5 energy industrial sectors which are disaggregated to final demands for 16 energy products.
  b. Technical coefficients for the nonenergy industrial sectors. Using a fixed distribution of intermediate demands for the products of the 5 energy sectors to energy product categories, determine demands for 16 energy products by the nonenergy sectors.
  c. Prices of primary inputs and nonenergy industrial products.

  Using the solution to BESOM determine:

  d. Technical coefficients for all energy sectors of the integrated model.
  e. Energy resource prices and energy product prices.
  f. Given technical coefficients (b. and d.) and final demands (a.), determine levels of output for all 51 sectors of the integrated model.
  g. Given prices and costs (c. and e.), convert the array of interindustry transactions (f.), final demands (a.), and primary inputs into current prices.

- Step 2

  h. Generate data for BESOM:
     Production constraints on supplies of energy resources correspond to levels of energy resource output (f.). Demand for energy products corresponds to levels of energy product output (f.). Unit conversion costs (sum of operating and capital cost) from production model (LITM) and data input.
  i. Solve BESOM, which renders cost minimizing levels for the energy conversion processes and value maximizing (shadow)prices of energy resources and energy products.

- Step 3

  j. Determine prices for products of the 5 energy sectors of LITM from BESOM (i.).
  k. Given these prices, the prices of primary inputs (exogenous), and the level of productivity in each of the nonenergy sectors (exogenous), determine prices for the products of the nonenergy sectors, using the price possibility frontiers from LITM.
  l. From energy and nonenergy prices and the prices of primary inputs, generate the technical coefficients for the nonenergy industrial sectors in the integrated model.
  n. On the basis of these prices, allocate total consumption expenditures among the products of the 9 sectors of LITM and primary inputs.

- Step 4

  Return to step 1 until the solution obtained is equal to the solution from the previous iteration.

Additional information

Since the solution algorithm is quite complicated, an account from the authors on some characteristics of the solution is added.

(Hoffman and Jorgenson, 1977)

A solution of the integrated model consists of a solution of the expanded interindustry model for which the following conditions hold:
- The energy conversion levels minimize cost for the corresponding levels of energy demands and supplies, and for the corresponding unit costs of the energy conversion processes (i.).
- The prices of energy resources and energy products maximize the value of the products less the value of the resources (i).
- The prices of the 5 fuel types in LITM are generated by dual solution of BESOM (j.).
- The prices of the nonenergy products are consistent with the energy product and fuel prices and the exogenously given prices of primary inputs (k.).
- The unit costs of the energy conversion processes are consistent with nonenergy product prices and prices of primary inputs (h.).
- The technical coefficients for the energy sectors are those associated with the cost minimizing solutions of BESOM; the technical coefficients for the nonenergy sectors are those associated with the prices for primary inputs, the nonenergy products, and the 5 fuel types (l.).
- The final demands for energy and nonenergy products are those associated with the prices for these products (m.).

Under these conditions the value of the output of each sector of the expanded interindustry model is equal to the value of the input of that sector.

(Based on Hoffman and Jorgenson, 1977)

3.8 LITM linked to an optimization and an input-output model

Introduction

A description of this linkage is included because the interface is different from the LITM/BESOM integration, and because of the incorporation of an input-output-model. This model is an integrated model consisting of coupled submodels.

Description of submodels

TESOM

The Time-stepped Energy System Optimization Model (TESOM) optimally allocates energy resources and products and selects the least-cost mix of supply, conversion, and demand technologies to satisfy a specified set of energy demands. TESOM is very similar to BESOM, except in that TESOM incorporates time. The TESOM model provides a 'vintage' representation of the energy system in that the optimal levels of the decision variables for any time period are determined from the optimal levels established for previous periods; the retirement and deterioration rates, the lifetimes, and the associated costs of vintage capital stocks; and economic and technological factors affecting the feasible level of the decision variables for the period under investigation. Mathematically, the model is formulated as a sequence of linear programming formulations; one for each time period.

Input-output model
The BNL/Illinois input-output model differs from conventional input-output-models in the following ways:

- It contains energy sectors whose output is expressed in physical units (Btu) instead of dollar values.
- Outputs of the energy supply/conversion sectors are distributed to energy service sectors instead of directly to consuming sectors.

This model forms an 'integrative interface', according to Goettle et al.

Description of linkage

The models are not modified; the linkage is established by an iterative procedure. Figure 3.8 provides some more details on the interactions.

Algorithm

Goettle et al (1979) give the following account of the integration/solution procedure. First, depending on assumptions and scenarios, energy demand levels are estimated. Then TESOM is solved, subject to these initially determined levels of energy services. The solution values of energy prices, capital requirements, quantities, imports, and the levels of new energy technologies are entered into LITM which is solved to yield specific estimates of the level and composition of production and spending throughout the economy. Economic sector activities and the energy input per unit of economic activity are transformed by a 'reduced form' version of the input-output-model into a set of demands for energy services in physical units. Mathematically, these adjustments to the level and structure of the service demands are determined by accounting for the following:

- Changes in the supply levels due to changes in the level and composition of economic activity.
- Changes in the supply levels due to the changes in the energy input per dollar of output for each producing or consuming sector. This accounts for the substitution of nonenergy inputs in production and consumption.
- Changes in the demand levels due to efficiency improvements (from TESOM solution).

These energy demands are inserted in TESOM again, and produce a new simulation of the configuration of the energy system. This iterative process continues until consistency between the energy and economic systems in the two models is attained.

Additional information

The combined model system was used for an exploration of the role of energy in the U.S. economy. The projection provided a consistent and comprehensive view of the details of technological and interfuel

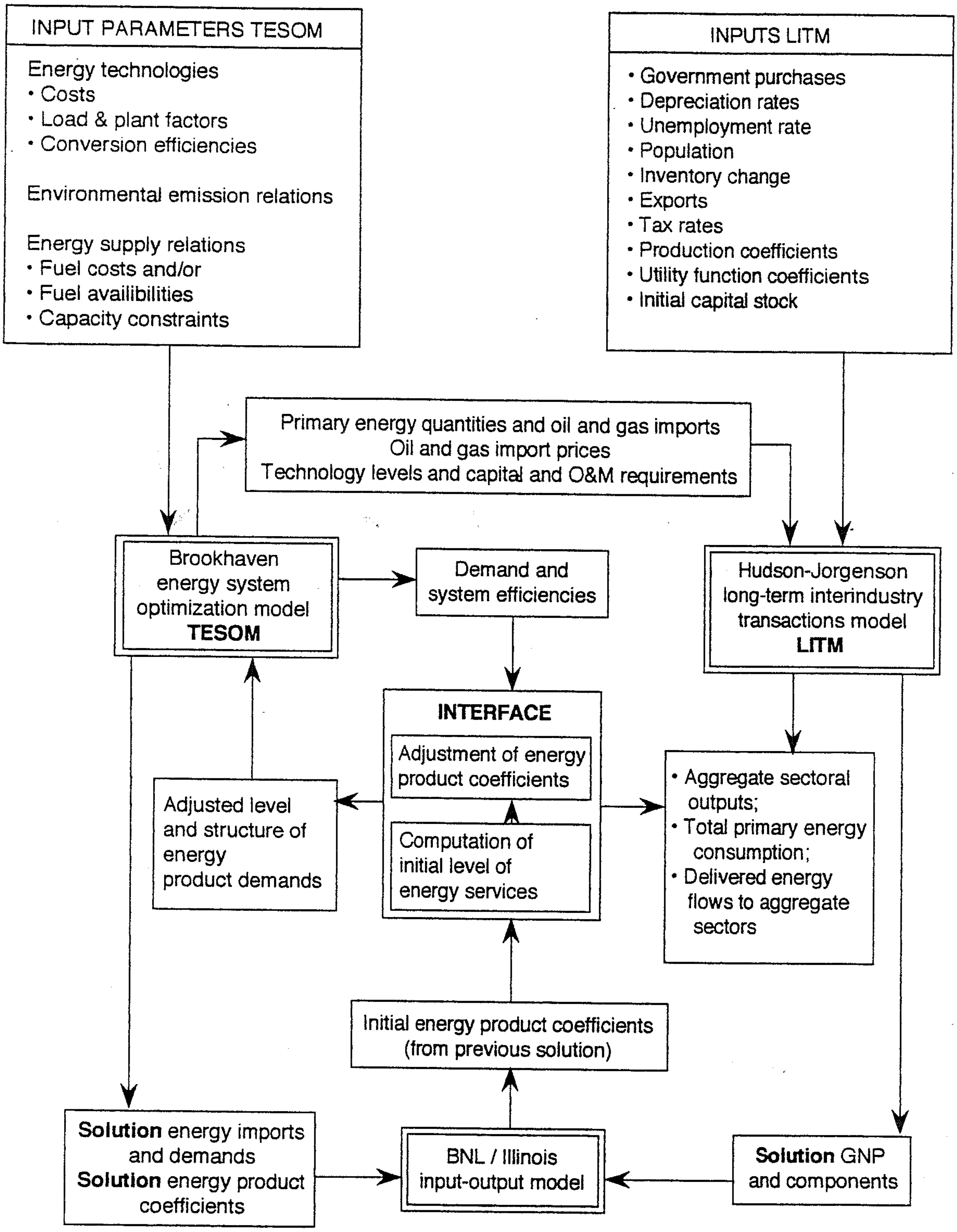


Figure 3.8 *The LITM/TESOM/Illinois combined model system (adapted from Goettle et al, 1979)*

substitutions in the energy sector, variations in the pattern of inputs for production, and product and compositional changes in final demand spending.

(Based on Groncki and Marcuse, 1979)

3.9 A short description of other integrated models

MARKAL-MACRO

The MARKet ALlocation model (MARKAL) is an energy system model, which determines the optimal mix of technologies to satisfy useful energy demands, subject to specified costs and constraints. The model uses (non)linear programming, and minimizes costs. It includes detailed technical information.

The model optimizes the energy system for the period 1980-2020 simultaneously in 9 steps of 5 years each. For the linkage this has been changed to 4 steps of 10 years each. This simultaneous optimization can be called dynamic or perfect foresight, and assumes policymakers know all about the future

(Okken et al, 1991)

MACRO has been described in section 3.4. The production function has been modified before linking with MARKAL. Gross output now depends on three inputs: capital, labour, and useful energy demands. The production function has a nested CES (constant elasticity of substitution) form which makes the model incorporate price-induced energy conservation. In addition, there are parameters that represent 'autonomous improvements in energy efficiency'.

MARKAL-MACRO is an integrated model consisting of fully integrated submodels, and forms a dynamic nonlinear optimization model.

The objective function comes from MACRO: the maximand 'utility'. This is the sum of discounted logarithms of consumption.

There are two kinds of constraints incorporated: binding and non-binding rows. Non-binding rows are:
- 'Linkage equations' that determine the impact of the MARKAL variables upon the total energy costs (this is a MACRO variable) in period t.
- 'Linkage equations' that link the MARKAL supply activities to the MACRO demand variables. In MARKAL a fixed demand is associated with each form of useful energy during each time period. In the linked model, these demands are treated as decision variables. The energy supplies are related to the MACRO demand variables through a zero-one table of demand correspondence coefficients.
- MARKAL's objective function (cost minimization).
- The accounting equations of MARKAL.

Binding rows are:
- The other MARKAL equations.
- The MACRO equations.

While MACRO is written in GAMS, MARKAL is written in OMNI. A conversion program is used to convert the MARKAL matrix to GAMS. The main program is written in GAMS and solved using MINOS (reduced gradient optimization).

(Manne and Wene, 1992)

The IIASA model system

The IIASA Energy Program was a large research project initiated after the 1973 oil embargo. It lasted 7 years and involved more than 140 scientists from 20 countries. The final report, 'Energy in a finite world' had a considerable impact among both scientists and policymakers.

The IIASA system consists of three component models and a lot of informal procedures (assumptions, judgements, manual calculations). The formal mathematical models are linked together in an iterative loop. This loop begins with MEDEE-2, an energy demand model, which uses initial assumptions about economic growth, population projections and lifestyle parameters to determine energy demand levels. The optimization model MESSAGE computes the least expensive supply strategy that meets the demand levels produced by MEDEE, subject to constraints on resources and technology. This strategy is then inserted in IMPACT that calculates requirements for capital investment, labour, land, water, etc, and assesses environmental impacts.

Originally, the next step in the iteration was planned to be the feedback from IMPACT to MEDEE-2 to 'close the loop', but this has never been achieved. It could not be implemented, so the iteration only involved MEDEE-2 and MESSAGE, which had little effect.

Keepin and Wynne (1984) re-examined the results and conclusions from the project, and conclude that the influence of the formal models was very small, thus leaving a lot of space for subjective assumptions and judgement. They state: 'Despite the appearance of analytical rigour, IIASA's widely acclaimed global energy projections are highly unstable and based on informal guesswork. This results from inadequate peer review and quality control, raising questions about political bias in scientific analysis.'

(Keepin and Wynne, 1984; Lakshmanan and Johansson, 1985)

IFFS

The Intermediate Future Forecasting System (IFFS) is organized along fuel lines. The model consists of a central integrating procedure, and electricity, oil, gas and coal markets modules. The model operates iteratively to balance supply and demand for all fuels at market clearing prices. The central integrating routine calls all of the modules in turn, repeating the sequence until all prices and quantities converge to an equilibrium. When called, a fuel module computes a supply/demand balance for that fuel and then returns to the integrating routine. The algorithm used is related to the Gauss-Seidel algorithm for solving simultaneous equations.

(Murphy, 1983)

SEAS

The strategic environmental assessment system (SEAS) model is an integrated economy-environment-energy model. The core model is a 200--sector dynamic input-output forecasting model called INFORUM, which is linked to a macroeconomic model. The 200 sectors are disaggregated into many more product and technological subsectors in the INSIDE module, which calculates different pollutant emissions. The ABATE module computes the costs of pollution abatement for feedback to INFORUM, where the economic impacts are obtained.

The energy subsystem comprises of an 'energy supply network simulator', three end-use energy demand models, and an energy investment model. The investment requirements corresponding to the energy supply technologies feed back to the energy demand models and INFORUM.

The REGION model converts national economic and pollution forecasts into geographical areas.

(Lakshmanan and Johansson, 1985)

3.10 Summary and overview

In the following table, a summary is given of all models that have been described in sections 3.1 to 3.8. The framework that was used in these surveys also can be recognized in this table. It provides a quick overview over the models, their common features and differences. It must be stressed, however, that the models cannot be compared too well because they were made for different purposes and differ a lot in their level of detail and in what they describe. Their only similarity lies in that they are all integrated models in one way or another.

In this table also the linkage and convergence properties are indicated, using the terminology of Capros et al., introduced in chapter 2. The linkage properties give information about the treatment of time in the integrated models. If these terms are not applicable, they are omitted. To avoid confusion, the linkage and convergence properties are given in italics.

Model name, scope	Types of component models	Linkage methodology *kind of linkage*	Algorithm *kind of convergence*	Policy issues addressed
PIES energy sector model	econometric demand model *and* various supply models *and* lp-model	consisting of coupled submodels: 'integrating model' (lp) combines supply and demand *static model*	approximation to fixed-point algorithm for partial equilibrium *numerical*	U.S. dependence on oil imports, impact of price controls
SRI-Gulf energy model energy sector model	2700 process models describing energy production, conversion, demand, etc	consisting of coupled submodels: process models are linked in a network describing interactions *intertemporal*	iteration up and down the network and adjustment of prices and quantities *numerical*	analysis of: synfuels strategy by Gulf Oil; U.S. energy resources development
ELIAS-ENMARK economy-wide integrated model	a computable general equilibrium model *and* an energy sector model (nlp)	consisting of fully integrated submodels: in one optimization model	solver for non-linear programming models *numerical*	analysis of the role of nuclear power in Sweden
ETA-MACRO economy-wide integrated model	an energy sector model (nlp) *and* a macro-economic growth model (general equilibrium)	consisting of fully integrated submodels: in one optimization model	MINOS: reduced gradient optimization *numerical*	estimation of the extent of linkage between GNP growth and energy use; analysis of costs of CO_2 emission limits
HERMES-MIDAS economy-wide integrated model	neo-Keynesian macro-economic model *and* combination of econometric demand/supply models of energy sector	consisting of fully integrated submodels: modification of both models, using framework HERMES *dynamic*	convergence procedure in TROLL *numerical*	medium term energy policy analysis and forecasting
LITM economy-wide integrated model	variable coefficient I-O model *and* a model of consumer demand driven by a macro-economic growth model	consisting of fully integrated submodels: one econometric model, system of equations	variation of Newton's method for systems of simultaneous equations *numerical*	analysis of the relation between economic growth and energy use
LITM-BESOM economy-wide integrated model	LITM (general equilibrium) *and* an energy sector model (lp)	consisting of coupled submodels: modified LITM *probably static linkage*	iterative solution method *empirical*	analysis of U.S. energy research, development, and demonstration policy
LITM-TESOM-BNL Illinois input- output model economy-wide integrated model	LITM *and* dynamic energy sector model (lp) *and* input-output model	consisting of coupled submodels: linkage established by iterative procedure *intertemporal*	iterative procedure *empirical*	long-range energy-economy projections

4. SUMMARY AND CONCLUSIONS

This research has been carried out in order to investigate model integration. In this concluding chapter, the goals that have been set in the introduction are reviewed using the results of the survey. Conclusions regarding the gains and drawbacks of model integration are drawn, and some pitfalls for designers of integrated models are identified. The importance of transparency in models is stressed.

4.1 Results

General background

The first goal was to give an overview of what is reported in general on these models. That was done in chapter 2, by giving a conceptual framework.

The presented roles of integrated energy models show the most important advantage of integrated models; the framework they provide to study energy-economy interactions in a consistent way. This advantage also was the prior motivation for this survey on integrated models.

It appears that three inducements for developing and using integrated models can be found in recent history.

- Uncertainty about energy prices, which originated in 1973 during the first oil embargo.
- The limitations of stand-alone energy sector and macroeconomic models, which had been used for energy policy analysis before.
- Environmental concern, which gave rise to the development of models studying energy-economy-environment interactions.

A recent use of integrated models is to describe the economies in Eastern Europe, where both the economy and the energy sector are being restructured. Integrated models possibly can capture and show some of the complicated interactions.

For the sake of clearness, two classifications were presented by which integrated models can be distinguished and named. This was necessary because in literature many different terms are used, which can lead to confusion. Integrated models can be classified along their structure into two groups:

- integrated models consisting of coupled submodels;
- integrated models consisting of fully integrated submodels.

According to their scope, integrated models can be divided in:

- economy-wide integrated models;
- energy sector models.

Some more remarks could be made on integrated models consisting of coupled submodels.

Concerning the treatment of time in these models, a distinction was made between:
- intertemporal linkage, where in each iteration all time periods are considered, and
- dynamic linkage, where convergence is achieved per period.

Concerning the role of the interface module, the following tasks were identified:
- transformation of link variables;
- establishing consistency between different definitions, representations, and aggregation schemes employed in the component models.

Desirable features for these models are for instance a consistent underlying theory, a modular design, and the availability of efficient solution methods.

Finally, the warning was given that the integration of models causes increases of costs, complexity, and data requirements. This holds for all integrated models, independent of their structure and scope.

Description of examples

The second goal was to describe examples of integrated models. The following eight models have been described in the third chapter: The Project Independence Evaluation System, the SRI-Gulf energy model, the ELIAS-ENMARK integrated model, ETA-MACRO, the HERMES-MIDAS linked system of models, the Long-term Interindustry Transactions Model, the previous model linked to BESOM, and the previous model linked to TESOM and an input-output model. Also, a short account of some other integrated models was given. In the surveys was tried to find a balance between completeness and readability.

In each model description, attention has been given to the component models, the linkage methodology, the solution algorithm, and the uses of the models. In section 3.10 a table is presented in which a complete summary of the described models is given. This table provides a quick overview over the models, and an opportunity to compare their features. It is not possible to compare the models completely, however, because they were developed for different purposes.

Of the eight surveyed models, two are energy sector models and six are economy-wide integrated models. The second group is slightly more relevant, because obviously energy-economy interactions can be represented better in economy-wide integrated models with energy sector detail.

Furthermore, four of the models are integrated models consisting of coupled submodels, and four are integrated models consisting of fully integrated submodels. The remark must be made, however, that within these groups of models, the differences in methodology are large. Five of the described models make use of optimization in one way or another, often using results from welfare economics.

Another goal was to find out what kinds of models were used as component models. The integrated models described were made up of the following component models:
- econometric demand models;
- econometric supply models;
- econometric 'process models';
- linear programming supply models;
- nonlinear programming energy sector models;
- (variable coefficient) input-output models;
- macro-economic growth models;
- general equilibrium models.

Linkage methodology

A goal of this research was to examine the linkage methodology. The survey has not identified one major linkage methodology, useful for linking any model with any other model. This would have been impossible, regarding the differences between the surveyed models, their scope and uses.

Only a relation between linkage methodology and structure can be pointed out:
- Integrated models consisting of coupled submodels are linked using interface modules which perform the transformation of link variables, and establish internal consistency.
- In integrated models consisting of fully integrated submodels, the linkage methodology is contained in the careful embedding of component models in one common framework.

Solution methods

Concerning solution methods, two main groups can be distinguished.
To solve integrated models consisting of coupled submodels, iterative procedures are developed that visit alternately the component models, solving and resolving them while checking and updating values of the variables on the connecting links. Their convergence properties have to be examined, so this procedure can be called empirical, established by the user. The PIES algorithm is an example of an algorithm that was developed especially for one integrated model, but proved to be suitable for the solution of many problems.

In integrated models consisting of fully integrated submodels, mostly an existing algorithm can be used. Often the convergence is numerical, established by the algorithm.

4.2 Pros and cons

For the sake of clearness, the advantages and disadvantages of integrated models are discussed separately for each category.

Integrated models classified along their scope

Integrated energy models are powerful tools for policy analysis. Compared to stand-alone models, the advantages of economy-wide integrated models are the following. They provide a framework in which the interactions between the energy sector and the rest of the economy can be represented and studied. In particular the role of prices and market behaviour can be considered, which is something energy system models don't consider. Compared to stand-alone macro-economic models, economy-wide integrated models provide more energy sector and technological detail. Thus, the degree of realism is enhanced, and market interactions and market dynamics are better simulated.

The energy sector models PIES and SRI-Gulf, though not giving feedback to macro-models, incorporate more detail than ordinary energy sector models and are well suited to assess the consequences of energy policy.

There are also disadvantages to the use of integrated models. When combining techniques, the complexity of a model increases, so large investments of time and resources are required. Consequently, the costs of both development and use of an integrated model are higher. The data-requirements of an integrated model are large, and since a model that is used also has to be maintained and updated, the data-requirements have to be fulfilled more than once. Another consequence of increased complexity can be a loss of transparency, which will be discussed later in this chapter.

These disadvantages apply to all of the described models, and make it necessary to balance carefully the costs and benefits. For some purposes, using integrated models may be 'overkill'.

Integrated models consisting of coupled submodels

A methodological advantage of integrated models consisting of coupled submodels can be that combinations of techniques can compensate weaknesses of one approach with strengths of another. For instance, the dynamic input-output coefficients derived from the producers models in LITM improve the model's forecasting ability when compared to traditional input-output models. In PIES, demand and supply sides of the energy market are modeled using the most appropriate methodology for each component. This idea has been elaborated most extensively in the SRI-Gulf model.

However, model integration by coupling submodels can harm the transparency of the model, so that newcomers won't understand the model quickly, and the model is more prone to mistakes. This has been treated in different ways in the models described. SRI-Gulf and PIES have a logical structure, in which the submodels represent processes that also are separate in real life. Their solution methods iterate in a 'logical' sequence. LITM and LITM/BESOM, on the contrary, have become large-scale econometrical models which aren't seen through at first glance.

Integrated models consisting of fully integrated submodels

The advantage of offsetting the weaknesses of one technique with the strengths of another clearly doesn't hold for integrated models consisting of fully integrated submodels. The component models mainly give up their separate structure to be integrated in one common model framework. And the weaknesses of the methodology chosen cannot be offset, which is another drawback. So this methodology is just as flexible as the model framework chosen, which is probably less flexible than a combination of techniques.

Still another drawback of this methodology is that it is often hard to trace back if the integration has been carried out correctly, and whether the behaviour of the component models has been preserved.

Full integration also yields a lot of benefits, however. Because an existing modeling framework is chosen (in the models described: optimization), solution methods are available, and their convergence properties are known. This reduces the costs of development. There is also more knowledge of what can and cannot be done using that specific framework.

4.3 Pitfalls

A pitfall for all designers of integrated models concerns the important aspect of model linkage presented by Boyd et al., the 'common set of assumptions'. It is very important to give attention to the possible consequences of linking models that have been separately estimated. And without consistent data, the output of any model is worthless. Capros et al. explicitly checked this when developing HERMES-MIDAS.

And even the possibility of not being able to establish the linkage at all does exist. Keepin and Wynne (1984) report that in the IIASA model set eventually the model that was supposed to close the loop only served as a 'monitoring model'. Despite sincere efforts, the iterative procedure that had been planned could not be implemented. Probably this occurs more often, as Cofala et al. (1990) observe the tendency to diminish the role of formal models in favour of expert judgement because of these problems.

Other possible sources of problems (which were encountered by Lundgren) are:
- When models have different commodity classifications. This can be overcome with aggregation rules.
- When models have different treatments of investments.
- Different units of measurement in the models. A parameter can be introduced which converts from prices to physical units.
- When the sectoral classifications or the capital accumulation systems of the component models are not consistent.

4.4 Requirements

Component models

To establish a successful linkage, it is sensible to choose component models that are as consistent as possible in commodity classifications, treatment of investments, sectoral classifications and capital accumulation systems. That reduces the amount of work needed to modify the submodels and to develop interface modules, or to embed the component models in one model.

Transparency

Some remarks already were made on transparency. Lack of transparency appears to be a weakness of most integrated models, which is a logical consequence of the increased complexity of any combination of models.
However, everything should be done to make integrated models as transparent as possible for the following reasons.

- Outsiders should be able to audit and understand integrated models, because important conclusions are drawn from their output.
- To facilitate development and maintenance. A complex model is more prone to mistakes.
- It should be clear which part of reality has been modeled, and which questions are addressed.
- From the model statement, one should be able to draw conclusions on behavioral assumptions underlying the model.
- The interpretation of results of integrated models should be as straightforward as possible.

One way to establish transparency is a modular design. A modular structure makes it easier to modify or expand submodels without significant changes in the overall model structure. Moreover, a modular structure provides for insight in the functioning of the component models, and thus facilitates control and interpretation.

Obviously, integrated models consisting of coupled submodels come closer to this ideal than integrated models consisting of fully integrated submodels. However, in practice models like LITM and linkages of LITM to other models don't excel by transparency. Of the surveyed models, only SRI-Gulf has a real modular design. But one remark on this model was that it is not clear where in the model decisions are taken, which harms the transparency.

An advantage of integrated models consisting of fully integrated submodels can be that the common model framework is thoroughly known, so that the consequences of the integration can be assessed quite well.

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