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A linked model for energy-economy analysis**

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**Biomedical and Environmental
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Analytical Sciences Division

DEPARTMENT OF APPLIED SCIENCE

**BROOKHAVEN NATIONAL LABORATORY
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A linked model for energy-economy analysis**

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MARKAL

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MAT.INC
COST.INC
DEMAND.INC
MACRO.INC

1. Introduction

1.2. Purpose

MARKAL-MACRO is an experiment in model linkage. This new tool is intended as an improvement over existing methods for energy strategy assessment. It is designed specifically for estimating the costs and analyzing the technologies proposed for reducing environmental risks such as global climate change or regional air pollution.

The greenhouse gas debate illustrates the usefulness of linked energy-economy models. A central issue is the coupling between economic growth, the level of energy demands, and the development of an energy system to supply these demands. The debate is often connected with alternative modeling approaches. The competing philosophies may be labeled "top-down macroeconomic" and "bottom-up engineering" perspectives.

Do macroeconomic models, with their descriptions of effects within the total economy but fewer technical details on the energy system, tend to overestimate future energy demands? Conversely, do engineering models, ignoring feedbacks to the general economy and non-technical market factors but containing rich descriptions of technology options, tend to take too optimistic a view of conservation and the use of renewable energy sources? Or is the principal difference that the engineering models ignore new sources of energy demands, and that the macroeconomic models ignore saturation effects for old categories of demands?

An efficient modeling tool must have the scope and detail to match the width and depth of the policy problem being analyzed. If we are to cope with major environmental risks (e.g., the possibility of global climate changes), there must be long-range, fundamental changes in the energy system. For an analysis of these changes, the modeling tool must be able to capture the complex network of relations within the energy system, as well as the opportunities of new or improved technologies.

Changes in the energy system may lead to increased energy costs and changing relative prices for energy carriers. If energy prices rise, there will be a considerable amount of price-induced conservation. A transition would require the reallocation of resources from other parts of the economy. In this way, it could affect capital formation and reduce economic growth. Ultimately this would affect the aggregate level of economic activity and the mix of energy demands. To analyze these indirect effects of emission reductions, we need modeling tools that will integrate the macroeconomic and the systems engineering approach.

1.2. The Models

Good documentation is available for MARKAL and for MACRO. These each have a proven track record for energy and environmental use. See Rowe and Hill (1989), Johnsson et al. (1992) and Manne and Richels (1992).

Both models are dynamic. That is, they are solved under the assumption that there is perfect foresight with respect to changing technologies and economic conditions. The alternative would be to adopt recursive dynamics in which decisions are made separately for each time period. The recursive approach has several advantages, but like the cobweb model of agricultural systems, it has the disadvantage of a tendency toward "overshoot and collapse".

MARKAL is a systems engineering (physical process) analysis built on the concept of a Reference Energy System, RES. See Marcuse et al. (1976) and Fishbone et al. (1983). MARKAL allows a detailed description of existing and alternative energy technologies and of existing and alternative paths of energy carriers from their source — through different conversion technologies — until the point of final use. The MARKAL structure makes it possible to build in supply curves of technical conservation. See Wene (1980). Often, however, it was supposed that comprehensive supply curves were too difficult to estimate, and price-induced conservation options were therefore omitted.

MARKAL is solved by means of dynamic linear programming. In most applications, the end use demands are fixed, and an economically efficient solution is obtained by minimizing the present value of the energy system's costs throughout the planning horizon.

Generally, MARKAL has been used in a stand-alone mode, but there have been a number of experiments with informal linkage to other models. The first work along these lines was reported by Hoffman and Jorgensen (1977). For subsequent work, see Berger et al. (1987) and Yasukawa et al. (1989). We are unaware of previous efforts at formal linkage ("hardlinking") between MARKAL and a long-term macroeconomic growth model.

MACRO is a macroeconomic model with an aggregated view of long-term economic growth. The basic input factors of production are capital, labor and individual forms of energy. The economy's outputs are used for investment, consumption and interindustry payments for the cost of energy. Investment is used to build up the stock of capital. The model clearly distinguishes between autonomous and price-driven conservation.

MACRO is solved by nonlinear optimization. It uses the criterion of maximum discounted utility of consumption to select among alternative time paths of energy costs, macroeconomic consumption and investment.

MACRO is "dynamic" in the same sense as MARKAL: it uses look-ahead features for choices throughout the planning horizon. This implies, for instance, that the investment decisions lead to equal benefits for the consumer from an additional dollar's worth of current consumption and the future consumption generated by an additional dollar's worth of investment.

Both MACRO and MARKAL are based on the concept of a single representative producer-consumer. This means that there are no tax or subsidy wedges between the marginal costs of consumption and of production. Neither model provides a direct calculation of impacts on individual industries at, say, the two-digit SIC level. Hitherto, MACRO has been used only in conjunction with ETA, a highly aggregated Energy Technology Assessment model.

In describing the development of the energy system and providing information about energy costs, MARKAL fulfills the same role as ETA. MARKAL has considerably more technological detail than ETA, but ETA has a more sophisticated treatment of nonlinearities in the dynamics of market penetration. ETA features only 8 electric and 9 nonelectric technologies. There is little or no description of the conversion processes that lie between primary energy sources and the end-use demands.

The linkage experiment is based on a U.S. demonstration version of MARKAL - one containing about 15 supply technologies, 30 demand technologies and 10 different fuels. It also incorporate seasonal and diurnal variations in the demands for electricity and district heating. It distinguishes between 13 different useful energy demands. These are viewed as primary inputs into the MACRO production function.

The full-scale U.S. version of MARKAL currently contains descriptions of more than 100 technologies, and time is analyzed in five-year steps. To reduce computer time, this experimental version of MARKAL-MACRO has fewer technologies and fewer time periods. We use ten-year increments from 1990 through 2020.

Useful Energy Demands are exogenous parameters in the stand-alone MARKAL. As a result of the two way linkage, useful energy demands become internal parameters determined by macroeconomic growth and by conservation (both autonomous and price-driven). Capital accumulation and economic growth are affected by changes in energy costs, but interfuel substitution lies within the domain of MARKAL.

1.3. Organization of this report

Section 2 contains a more detailed descriptions of the MARKAL and MACRO models and the concepts underlying the linkage of the two models. Section 3 describes some of the technical difficulties that had to be overcome, and section 4 provides illustrative numerical results. The concluding section contains our suggestions for future work.

2. MARKAL, MACRO and the linkage approach

2.1 Overview of the linkage

Figure 1-1 provides an overview of the connections between the two components of the system. To minimize the need for structural changes in the two original models, we have introduced only two types of linkage. There are physical flows of energy from MARKAL into MACRO, and there are energy cost payments from MACRO into MARKAL. This is much the same approach that has proven itself in ETA-MACRO. The principal difference is that the physical flows of energy are defined here as "Useful Energy Demands". They are exogenous to the stand-alone version of MARKAL, but endogenous to the linked model. The costs of energy supply appear in the objective function of MARKAL, but enter into MACRO through the period-by-period constraints governing the allocation of the economy's aggregate output between consumption, investment and energy cost payments.

The linkage between MARKAL and MACRO is based upon one key idea — the concept of an economy-wide production function. Just as with any other attempt at understanding the complexities of an economic system, there are pros and cons in adopting this particular abstraction. The principal advantage is that this enables us to make a direct link between a physical process analysis and a standard long-term macroeconomic growth model. The principal disadvantage is that we cannot make a direct connection with the interindustry composition of demands (described, for example, in terms of two-digit SIC codes).

For demonstrating the feasibility of these ideas, the model is benchmarked against U.S. data for a base year of 1990, and the projections cover ten-year time intervals from 2000 through 2020. This is an intertemporal rather than a recursive system. Expectations affect the accumulation of capital over time. Savings and investment decisions are modeled through the maximization of discounted utility.

AN OVERVIEW OF MARKAL-MACRO

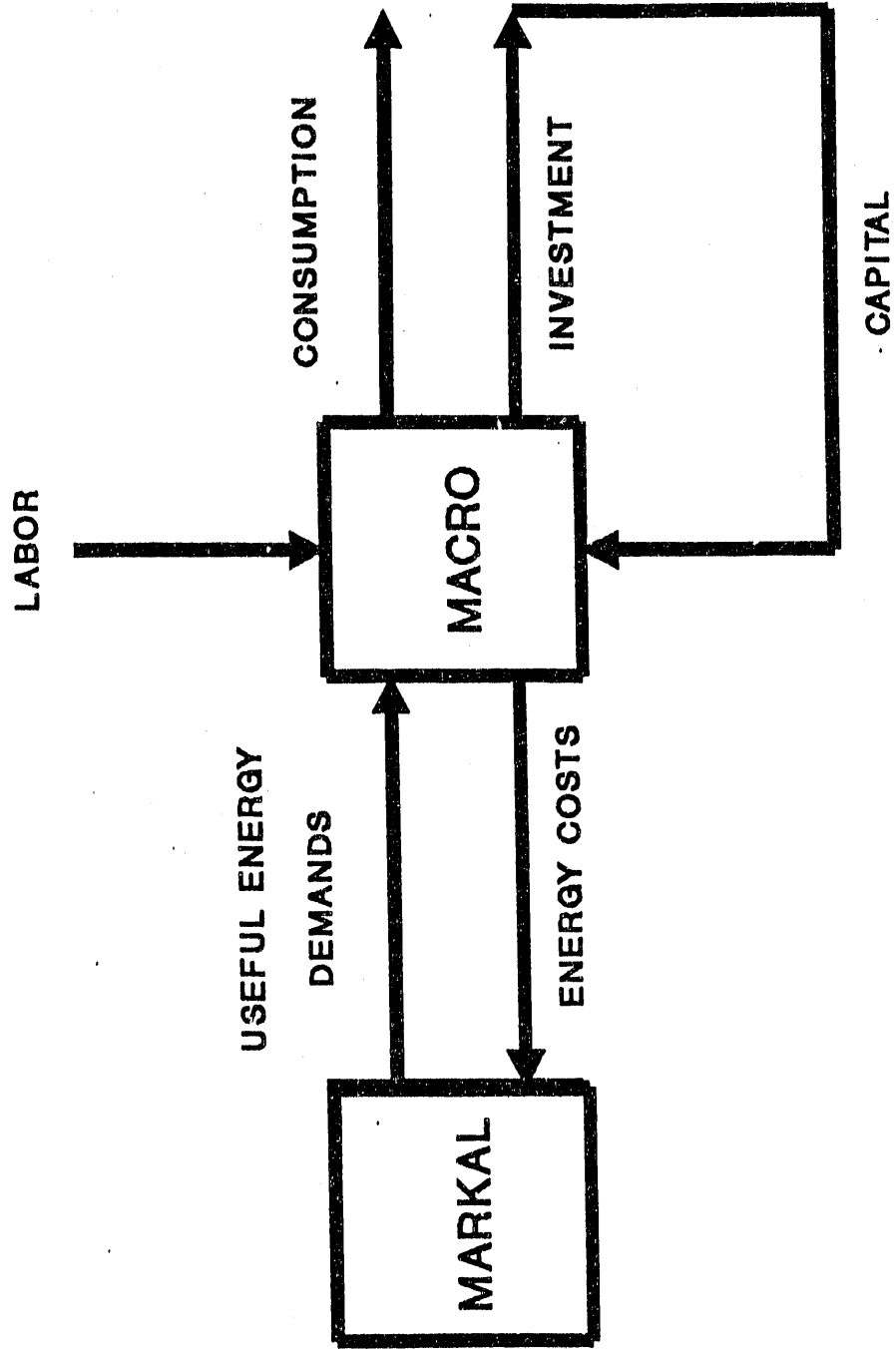


Figure 1-1. An overview of MARKAL-MACRO

2.2 MARKAL

The MARKAL (MARKet ALlocation) model was developed between 1976 and 1981 as a multinational collaborative effort within the framework of the International Energy Agency. See Fishbone et al. (1983). MARKAL is a technologically oriented linear programming model of the energy sector. The system boundaries are defined by the user. The model was used for studies of the national energy systems for most countries within the IEA. See Tosato et al. (1984). It was also used to support energy planning in developing nations such as Brazil, China, Ecuador and Indonesia. It was applied to regional energy systems in Canada and community energy planning in Sweden. See, respectively, Berger et al. (1987) and Wene (1989).

The RES (Reference Energy System) concept is central to MARKAL. The RES is a flowchart showing all possible routes from each source of primary energy through various transformation steps to each end-use demand sector. The flowchart can be extended to show emissions when energy is transported or converted from one form to another. MARKAL describes these routes, energy conversion and distribution technologies and also emissions control options. The model identifies those routes and technologies that best satisfy the overall objectives of the energy system. The model describes the technical and economic properties of each technology — and may also describe the technical and behavioral constraints upon their implementation. Typical parameters include energy efficiency, emissions, operating and maintenance costs, initial investment and availability factors.

The most common formulation is to satisfy the end-use demands at a minimum present value of system costs. Typically, the real annual discount rate lies between 4% and 8%. The modeling horizon is 25-40 years, usually described in time steps of either 3 or 5 years.

MARKAL is a data-driven model. The numerical results depend heavily upon the input assumptions. The logical structure is relatively simple. Most constraints describe annual, seasonal or diurnal energy balances. There are constraints ensuring that enough capacity will be built to meet the demands for secondary and tertiary energy carriers, and there are other constraints allowing for scheduled and unscheduled maintenance. The input data can be grouped into four broad categories:

- **Technology categorizations.** The scale may be either large or small. Both price-induced and non-price conservation may be included in the definition of a technology. A typical large-scale unit would be an integrated coal-gasification combined-cycle electricity generating station. Heat pumps and electric cars are examples of small-scale end-use technologies. Conservation options might include double-pane windows and high-efficiency oil burners. Technology characterizations represent most of the input data to a MARKAL model.

- Sources of primary energy. Primary energy may be defined in terms of oil and gas wells, coal and uranium mines, and biomass raw material. These sources are usually characterized by supply curves showing the annual potential supply and extraction costs. For exhaustible resources, there may be cumulative constraints indicating the total of proven reserves and additional resources that might be available over the planning horizon. Import and export options are also included here.

- Useful energy demands. In the stand-alone version of MARKAL, end-use demands are specified exogenously for all time periods. The demands may be defined either in terms of energy requirements or in terms of an energy service, e.g. vehicle-kilometers of automotive transport or tons of steel. The demands need not refer to a specific fuel. MARKAL has built-in options for alternative fuels and end-use utilization technologies.

- Environmental constraints. Environmental constraints may be introduced as a physical cap on emissions such as sulfur dioxide, nitrogen oxides or carbon dioxide. The dual variables on these constraints may be interpreted in terms of emission fees or taxes.

2.3 MACRO

The MACRO production function is characterized by *smooth* substitution. With its nonlinear form, a small price change leads to a small change in the mix of inputs or outputs. The structure leads to qualitatively different results from those generated by a linear program such as MARKAL. With linear programs, it is typical to observe "penny-switching" effects. A small change in prices will lead either to no effect whatever — or else to a large change in the composition of inputs or outputs.

The *inputs* to the production function consist of capital, labor and useful energy demands. Capital, labor and energy may each be substituted for the other, but there are diminishing returns to the substitution process. This is the way in which the model incorporates price-induced energy conservation. In addition, there is the possibility of autonomous improvements in energy efficiency (AEEI, for short). These are non-price factors that could reduce energy demands per unit of gross output.

To avoid the econometric estimation of many parameters, the production function is a nested CES (constant elasticity of substitution) form. At the top level, there is a capital-labor aggregate that may be substituted for an energy aggregate. At the bottom level, there is a unitary elasticity of substitution between capital and labor, and the energy aggregate is *separable*. This structure implies that capital and labor may be substituted directly for each other, e.g. through the automation of labor-intensive tasks. The higher the wage rate, the more attractive it becomes to adopt automation.

With this specific form of CES nesting, price-induced conservation operates by lowering the marginal productivity of capital and labor. That is, if there is a rise in energy costs, the production function allows us to adapt by substituting more capital and labor in place of energy. Moreover, each category of useful energy demands may be substituted for the other. In effect, we assume "want independence" between them. See Frisch (1959). The ease or difficulty of price-induced conservation is governed largely by the value adopted for ESUB (the elasticity of substitution between the energy and the capital-labor aggregates).

The economy's long-term growth rate is determined primarily by the value assumed for the growth of the labor force and its productivity. The combination of these two factors is described in terms of labor "efficiency units". For shorthand, this is the "potential" growth rate of the economy. It is a major determinant of the utility discount rate employed in the MACRO objective function. If there is a rise in energy costs, it will be optimal to reduce consumption and investment. With a drop in capital formation, the realized growth rate will then fall short of the potential.

3. The specifics of hardlinking

3.1 GAMS and OMNI

MARKAL-MACRO is written in GAMS (a generalized algebraic modeling system). See Brooke et al. (1988). To solve a single case, it takes about 6 minutes on a 25 mHz desk-top 486 computer. This is about 50% more time than is required to solve MARKAL as a stand-alone linear program.

MARKAL is written in OMNI, a character-oriented language, whereas GAMS is oriented toward the use of sets. The difference is subtle. OMNI is intended for applications in which the numerical entries may be varied, but the logical structure remains substantially unchanged. By contrast, GAMS is designed for use by those who are not computer specialists, but who place a high value on being able to change the model's structure.

The OMNI system generates the entire linear programming matrix of MARKAL in a standard MPS (mathematical programming system) format, but GAMS was not designed so as to be able to read this format directly. Instead, a special MPS to GAMS conversion program was written so that the MARKAL submodel could be taken over directly with a minimum number of changes. For further details on the model formulation and the conversion process, see Appendices A and B.

3.2 Treatment of capital charges

In earlier applications, the MARKAL and MACRO submodels differed in their terminal conditions and also in their treatment of capital charges. MARKAL viewed investments as one-time expenditures that provide a stream of capacities available during subsequent time periods. If it survives past the horizon date, an investment leads to a salvage credit during the terminal period. This is sometimes said to be a "dual" terminal condition.

By contrast, MACRO employs a primal terminal condition. It specifies that the rate of investment in the final period must be large enough to allow post-horizon growth to proceed at a constant geometric rate. It allows for investment costs through capital recovery factors — with a uniform annual amortization charge throughout the useful life of plant and equipment. To reduce horizon effects in the linked model, we adopted the MACRO conventions for post-horizon growth and for investment costs. Incidentally, even before the merger, both models were using the identical numerical value of the discount rate for investment purposes — 5% annually, as the real cost of capital (net of inflation) to the U.S. economy.

MARKAL and MACRO allow for the durability of capital goods, but each in a somewhat differently. In MARKAL, there is a fixed value assigned to the useful life of each distinct technology, and there is a uniform amount of capacity available from that investment during each year of its life span. There is an explicit distinction between the decision variables that govern investment and those that govern the use of capacity. In MACRO, this distinction is not drawn; depreciation is viewed as a geometric decay process — typically a decay rate of 5% annually. This reduces the number of decision variables and constraints and therefore reduces the time required for computations, but it means that we do not have the option of abandoning excess capacity in the form of obsolete capital equipment. In the linked model, we follow the original MARKAL formulation for the energy sector and follow the MACRO formulation for the economy-wide capital stock.

3.3 Benchmarking to base year data (calibration)

The MACRO production function contains a capital-labor term and an energy aggregate. The user must specify an overall elasticity of substitution between capital-labor and energy. Each of MARKAL's useful energy demands enter as inputs into the energy aggregate. For purposes of this demonstration, there were 13 demand categories. Thus, benchmarking involved estimation of a coefficient for the capital-labor term and for each of the 13 components in the energy aggregate.

To calibrate the MACRO submodel, the following base year data were required: GDP, aggregate energy costs, the demand and the price for each category of useful energy. Estimates must also be provided for the capital-GDP ratio, the depreciation rate, and capital's value share of GDP. The three latter parameters must be consistent with the net rate of return on capital that is assumed in the stand-alone version of MARKAL.

For purposes of this demonstration, the base year was 1990. The GDP was readily available from standard statistical sources. For 1990, the useful energy demands and prices were taken from the stand-alone version of MARKAL. These prices are the undiscounted marginal costs (also known as shadow prices) taken from the dual solution to this programming model. To illustrate the robustness of this benchmarking procedure, Table 3-1 compares the energy prices from the stand-alone MARKAL and the linked MARKAL-MACRO model. The two sets of prices differ slightly from each other, but are reasonably consistent. During the course of our experiments with MARKAL-MACRO, we have encountered instances where the primal solution is degenerate, and the dual solution is therefore indeterminate. Some of these difficulties are traceable to current practices for describing base year residual capacity in the MARKAL database. Solutions are indeterminate when the upper and lower bounds on activity levels are set too close to each other. Other types of difficulties arise when the demand and/or supply categories consist of heterogeneous rather than homogeneous items.

The MARKAL-MACRO calibration procedure gives the modeler some degrees of freedom in the choice of demand structure, but it also requires greater attention to the quality of the base year data. Current validation procedures must be extended to include base year economic activities such as the energy system's investment levels, import costs and export revenues.

Table 3-1. Base year energy prices generated by MARKAL and MARKAL-MACRO
 (1990 base year, prices in 1980 U.S. dollars per GJ)

Useful energy demand category	MARKAL \$/GJ	MARKAL-MACRO \$/GJ
I1 Iron and steel metallurgy	15.35	14.42
ID Industrial process heat	4.69	4.61
IE Industrial electricity	12.62	11.69
IZ Hydrocarbons for non-energy use	3.08	3.08
R1 Residential space heat	10.59	9.17
R2 Residential hot water	6.65	6.30
R3 Residential air conditioning	13.62	12.20
R6 Commercial space heat and hot water	9.79	9.60
R8 Commercial air conditioning	15.04	13.70
RA Residential and commercial appliances	12.91	11.81
T1 Rail/truck/bus transport	3.67	3.67
T4 Automobile transport	21.27	21.27
T9 Air and ship transport	10.07	10.07

4. Demonstration with a restricted U.S. database

These computer runs are intended to demonstrate some important aspects of the MARKAL-MACRO linkage, but the results are not yet ready to be used as the basis for energy strategy assessments. Some database revisions were made, but only to ensure a consistent benchmarking procedure. The revisions were necessary because some data design practices, which are both appropriate and efficient for the stand-alone MARKAL, may lead to erroneous results for MARKAL-MACRO.

We have taken an existing database, reduced it in size by using decades in place of five-year time intervals, and by combining some of the less important energy technologies, and then checked the performance of this aggregated model. The next logical step would be to use the experience from the demonstration case to revise the existing procedures for data management and for quality control. We recommend that these procedures be revised before enlarging the database to contain more detailed information about the energy system and technological options.

This demonstration relies upon the most current US-MARKAL database available at Brookhaven National Laboratory. In down-sizing the Reference Energy System, we have taken advantage of an existing data set developed for demonstration purposes. The energy flows for the 1990 base year were updated by using information from the Energy Information Administration. We revised the physical flows but not the cost data.

Our initial experiments with the linked model indicated that it was not sufficient to update the energy flows. The current practice of describing residual capacities had to be changed so that the MARKAL submodel would provide an appropriate estimate of the base year's capital charges. For purposes of this demonstration, we adopted a simple procedure for correcting the residual capacities. This procedure should be further refined and validated. We have not altered any of the technology characterizations that appeared in the database. Many of these estimates were updated during the past few years, but a thorough review would be desirable before proceeding further. Such a review would greatly facilitate future analyses.

In section 4.1, we focus on energy demands and costs. These constitute the interface between the two submodels. We try to disentangle the effects of economic growth and of changes in energy prices. The section also contains a comparison between the exogenous demand inputs to MARKAL and the endogenous demand outputs from MARKAL-MACRO. The comparison illustrates how the linked model can be used to investigate features such as demand saturation.

We have already mentioned the routines for dealing with residual capacity. We now discuss them in further detail, and show how they may distort the benchmarking (calibration) of the linked

models. MACRO incorporates price-induced and autonomous conservation through parameters that define an economy-wide production function. MARKAL describes all conservation in terms of specific technologies. To avoid double counting, it is important that common procedures be developed for both models. Section 4.2 describes the demand technologies and the representation of conservation. For further work, we recommend that price-induced and autonomous conservation be handled by the MACRO submodel for useful energy demands, and that interfuel substitution and technology switching be handled within MARKAL. After establishing a base case, one could reintroduce price-induced conservation options within MARKAL — but only for those demand categories for which there is inclusive and detailed information available.

Section 4.3 compares the primary energy demands and emissions of carbon dioxide from the stand-alone and the linked models. Most of the differences in demand for specific energy carriers are the direct consequences of differences in the projection of useful energy demands.

4.1 Two-way linkage

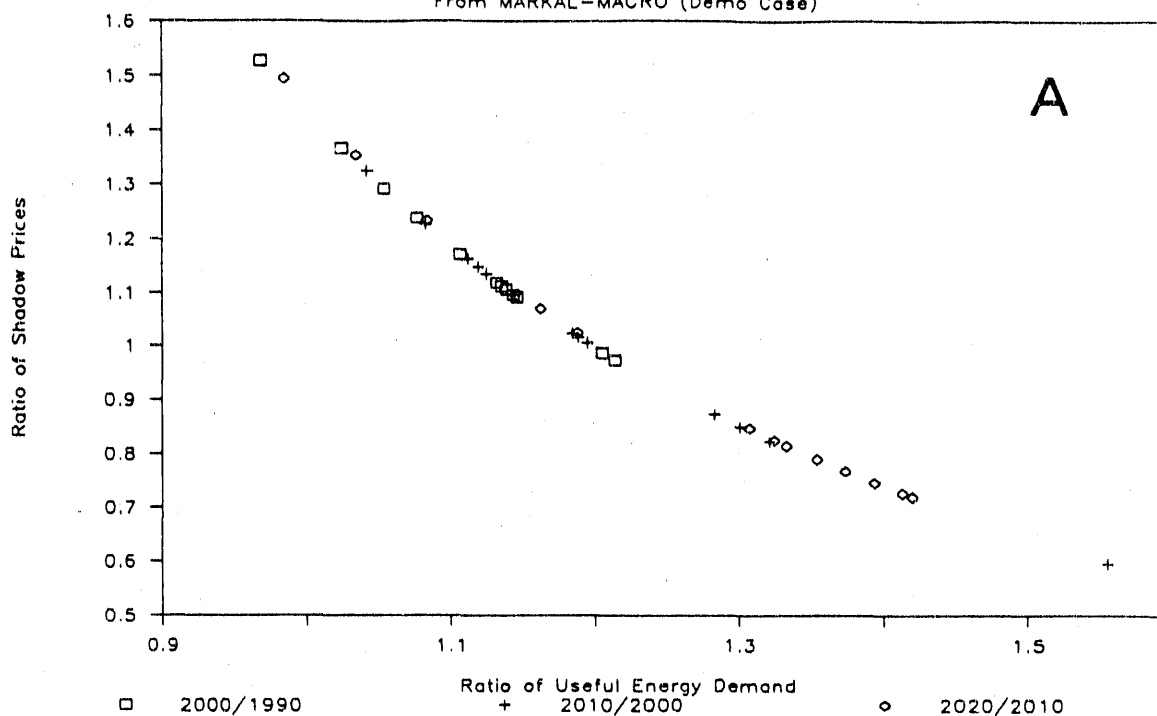
4.1.1. Economic growth and price-demand interactions

MARKAL is driven by exogenously given useful energy demands (UED). Critics often note that these demands are independent of prices. Although MARKAL will show how the different energy demands can be satisfied at the lowest possible cost, the level of energy services demanded from the energy system is independent of the price that the consumer must pay for these services. The model user may introduce technical conservation options as explicit activities. The demands may also be adjusted by external "add factors", but these are arbitrary and do not go to the core of the problem. The lack of demand-price interactions is particularly troublesome for national or regional models when we anticipate that there will be considerable changes in relative prices. CO₂ emission restrictions might well induce such price changes.

Figures 4-1A and B illustrate how the MARKAL-MACRO linkage affects the relation between energy demands, prices and aggregate economic growth. For each demand category, these figures show how marginal costs and useful energy demands (UED) change between the beginning and the end of each successive decade. The marginal costs for the demand categories are the same as those discussed earlier in section 3.3. The UEDs for MARKAL are taken from the exogenous demand projections. Those for MARKAL-MACRO are calculated endogenously, but they depend in turn upon the aggregate rate of economic growth, the autonomous energy efficiency increase (AEEI), the elasticity of price-induced energy substitution (ESUB) and the changes in energy prices.

CORRELATIONS SP AND UED RATIOS

From MARKAL-MACRO (Demo Case)



CORRELATIONS SP AND UED RATIOS

MARKAL: Exogenous UED, Endogenous S-P

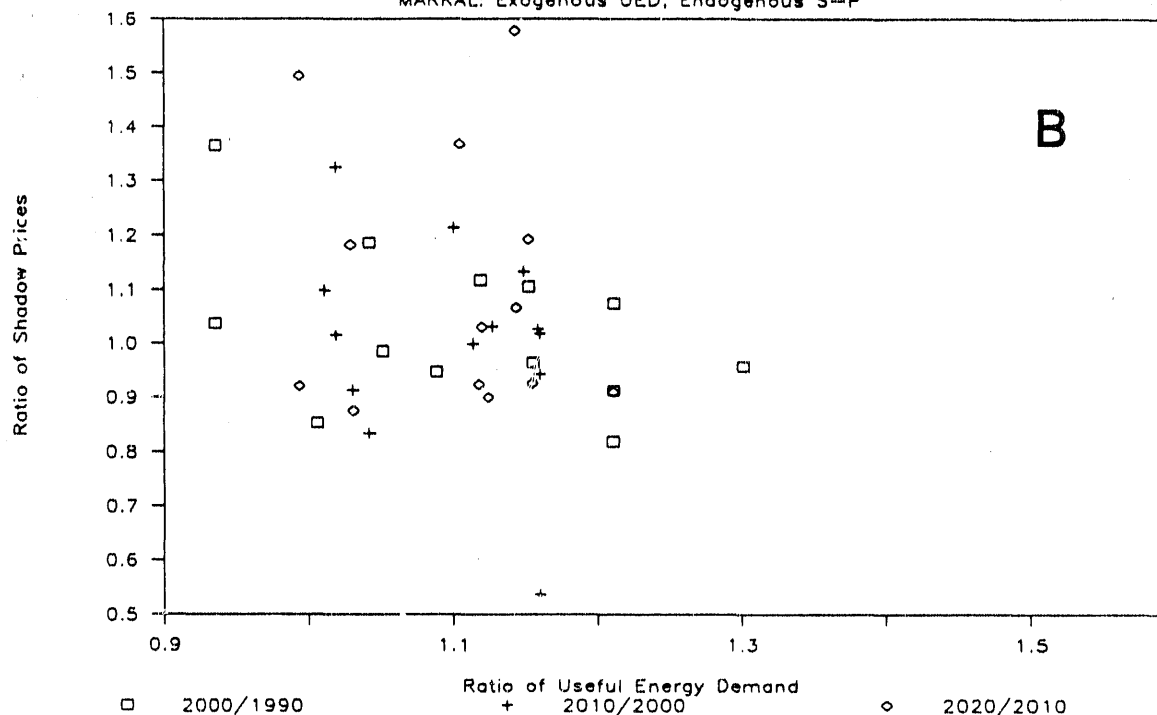


Figure 4-1A,B. Correlations between shadow prices and UED growth - three decades.

For each decade and each demand category, this figure shows the relation between the change in shadow prices (marginal costs) and the change in Useful Energy Demands. With three decades and 13 demand categories, there are altogether 39 data points. The top figure shows the results from the MARKAL-Macro demonstration case. The bottom figure shows the ratios for the externally specified demands and the internally generated shadow prices for the stand alone MARKAL model.

The MARKAL diagram shows no correlation between changes in marginal costs and changes in useful energy demands. By contrast, the MARKAL-MACRO diagram shows that all data points lie along curves that can be described by power functions. There are in fact three such curves, one for each pair of consecutive periods: 1990-2000, 2000-2010, 2010-2020. Figures 4-2A, B and C indicate that all results can be described by the same power function:

$$RUED(i,t) = A_i(t) * RMC(i,t)^{-ESUB}$$

where:

$i = 1, 2, \dots, 13$ is an index for the 13 categories of useful energy demands

$$RUED(i,t) = UED(i,t+1)/UED(i,t)$$

$$RMC(i,t) = MC(i,t+1)/MC(i,t)$$

$ESUB = 0.5$ = elasticity of substitution used in the aggregate production function

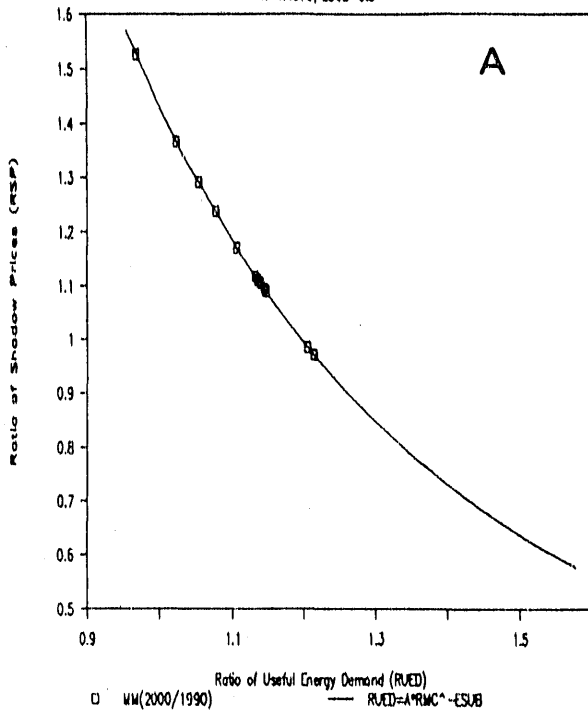
$MC(i,t)$ = marginal cost of energy for demand category i in time period t

$A_i(t)$ = production growth factor

The factor $A_i(t)$ depends primarily upon the aggregate economic growth rate, but it also depends on the AEEI factor assumed for demand category i . If energy prices remain constant, it would equal $RUED(i,t)$, the growth index between period t and period $t+1$. Thus, $A_i(t)$ shows how useful energy demand growth depends upon autonomous conservation and also upon aggregate macroeconomic activity. The power function term indicates how demand growth may be decoupled as a result of changing prices. In this example, we have assumed that the potential GDP growth rate is 2.0% annually from 1990 through 2020, and that there will be autonomous efficiency improvements of 0.5% in all demand categories. To a first approximation, we therefore expect all demands to grow by 1.5% annually. The actual demand growth rates $A_i(t)$ are a bit higher. They can be compared with the growth in the key macroeconomic variables shown in Tables 4-1 and 4-2. These growth rates are outputs from, not inputs to the MARKAL-MACRO model.

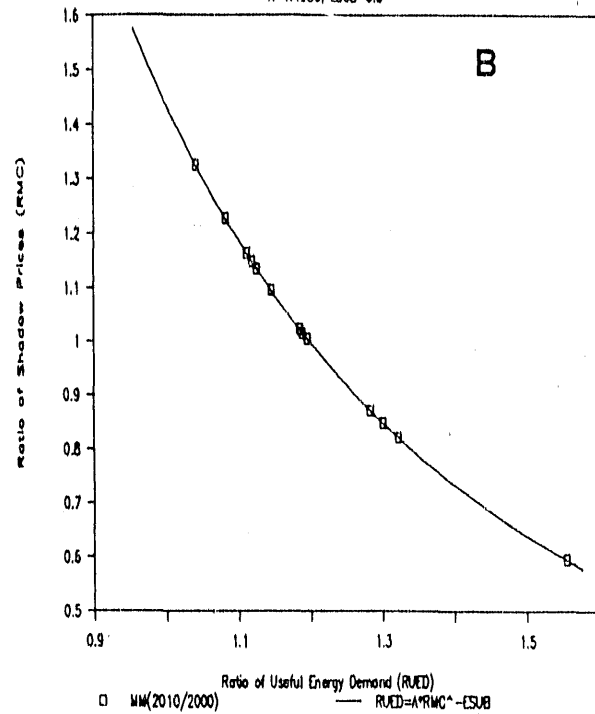
SP and UED Ratios 1990-2000

A=1.1975; ESUB=0.5



SP and UED Ratios 2000-2010

A=1.1986; ESUB=0.5



SP and UED Ratios 2010-2020

A=1.2034; ESUB=0.5

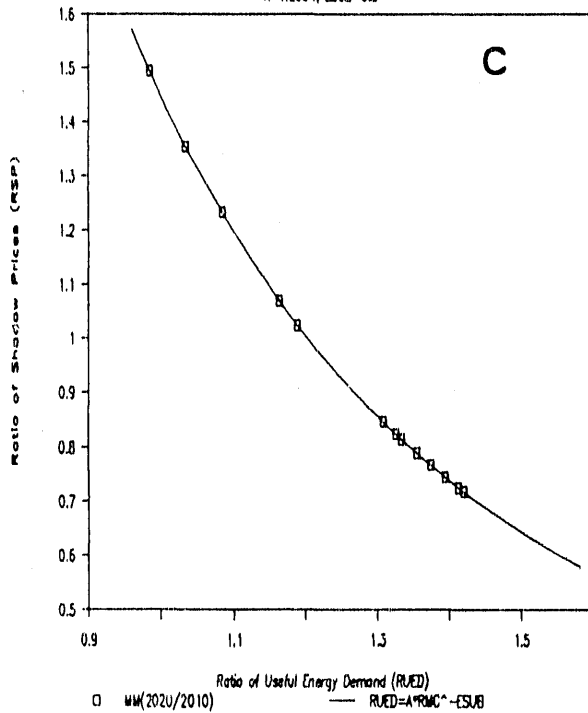


Figure 4-2A,B,C.

Comparisons between power function and MARKAL-MACRO results - by decades.

The lines are calculated from the power function and the squares refer to the MARKAL-MACRO demonstration. The MARKAL-MACRO results are sensitive to assumptions about the base year reference price. If there are large deviations from the power function that cannot be explained by differences in AEEI rates, the model user is advised to recheck the benchmarking procedure.

Table 4-1
Useful energy demand growth at constant energy prices

	1990-2000	2000-2010	2010-2020	1990-2020
UED				
growth factors	1.198	1.199	1.203	1.727
Annual growth rates, %	1.82	1.83	1.87	1.84

Table 4-2
Annual growth rates for macroeconomic variables, %

	1990-2000	2000-2010	2010-2020	1990-2020
Gross Domestic Product	2.04	2.16	2.28	2.16
Consumption	1.89	2.26	2.26	2.14
Investment	2.79	1.68	2.32	2.26
Energy Costs = EC	2.26	1.64	1.16	1.69
Gross Production = GDP + EC	2.08	2.08	2.12	2.09

There are various possible explanations for the discrepancies between the potential and actual growth rates of the macroeconomic variables. The decline in the growth rates for energy costs may be due to overoptimism in the MARKAL database about the prospects for increasing the efficiency of energy use. The MARKAL database itself contains assumptions about non-price conservation, and apparently the autonomous improvements are much larger than indicated by our explicitly specified AEEI parameter of 0.5% annually. A more detailed analysis of the production function shows that the rates $A_i(t)$ are affected by factors other than the GDP growth rate. They depend upon all four macroeconomic variables: gross production, capital, labor and energy costs. There may be other, more technical explanations for these discrepancies. For one thing, there could be slight changes in the results if we were to employ shorter time intervals — five years instead of decades.

For the initial experiments with the linked model, the database was updated only by revising the energy flows for the 1990 base year. In these runs, we observed an anomalously large growth in energy costs (4-5% annually) during the initial decade — and therefore a reduction in the rate of GDP growth. For several of the demand categories, there were exceptionally large increases in the marginal costs of energy supply. As a result, the useful energy demands and total primary energy consumption *decreased* between 1990 and 2000. The high growth rates for marginal and total energy costs were not the results of an increase in fuel prices or any other real change in the energy system environment. Instead, these growth rates were spurious effects caused by the representation of base year investments in the MARKAL database.

To understand these results, one must examine the stand-alone version of MARKAL. It is a tool for strategic investment analysis. It focuses on the possible decisions that are open to the decision maker. The energy flows during the base year are introduced as a reference point, but there are no investment decisions to be made in this year. All investments are treated as “sunk costs”, and all existing capacity is represented as residual capacity that requires no investment. The total energy costs for the base year will contain virtually no capital charges. There will therefore be demand categories where the shadow prices do not reflect the long-term marginal costs (including capital charges).

This treatment of residual capacity in MARKAL is efficient and well suited for the original model design. However, MARKAL-MACRO is calibrated by using base year data. If we exclude most investment costs during the base year, the calibration will be distorted. By understating energy costs, there will also be an understatement of demand growth during the initial decade.

For demonstration purposes, we have adopted a simple procedure to make the base year data consistent with the need for linking both the primal and dual demand variables in MARKAL-MACRO.

For each technology, we assumed that the base year investment is equal to the base year residual capacity divided by the lifetime of the technology. (This would be consistent with a steady state economy. If there is straight-line depreciation, the historically given capacities are retired at a constant rate.) The procedure works well for the demonstration case, and it leads to fairly consistent shadow prices. For future work, it would be desirable to refine this procedure, and to cross-check it against the investment statistics available for the energy sector.

4.1.2. Endogenous and exogenous demands

The MARKAL demand forecasts contain implicit assumptions on saturation effects, i.e., decoupling of GDP and demand growth. MARKAL-MACRO considers this as an instance of autonomous conservation, and it describes saturation effects through the Autonomous Energy Efficiency Increase (AEEI) parameter. This is an explicit and easily documented input assumption for any scenario.

For the demonstration case, we have assumed that the AEEI = 0.5% for all demand categories and time periods. In its present form, the model is designed so that the user is free to define scenarios where there is a different AEEI for each demand category. With a modest amount of additional GAMS programming, it would also be possible to allow for the AEEI to vary from one time period to the next.

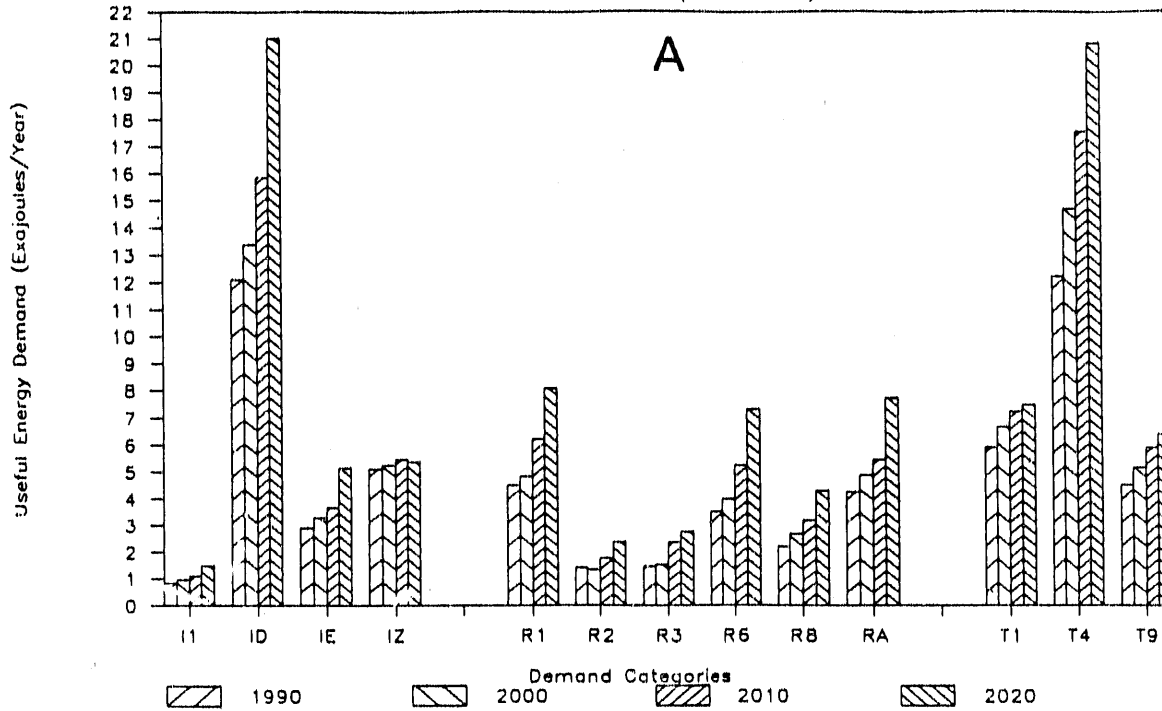
Figure 4-3A shows the useful energy demands calculated by MARKAL-MACRO, and Figure 4-3B provides a comparison with the exogenous demands that drive the MARKAL stand-alone model. These exogenous demands were derived by assuming a 2% yearly increase in GDP, i.e., the same as the potential GDP growth assumed for MARKAL-MACRO.

There are differences between the two models that can be traced to price-induced conservation. However, there are four demand categories where MARKAL-MACRO consistently generates larger demand growth than is assumed for stand-alone MARKAL: ID: "Industrial process heat", R1: "Residential space heat", R6: "Commercial space heat and hot water", and T4: "Automobile transport". In these demand categories, we would have to assume AEEI rates of 1.4% - 2.5% in order to have MARKAL-MACRO reproduce the demand assumptions used in MARKAL.

The MARKAL demand forecasts are usually based on bottom-up engineering calculations. For example, projections of the demand for space heat are usually based on models that involve assumptions on future building codes, climatic properties of building shells, rates of construction of new buildings and refurbishing or destruction of old buildings. They are also affected by socioeconomic

Useful Energy Demands

From MARKAL-MACRO (Demo Case)



Difference in Useful Energy Demands

MARKAL-MACRO less MARKAL (Demo Case)

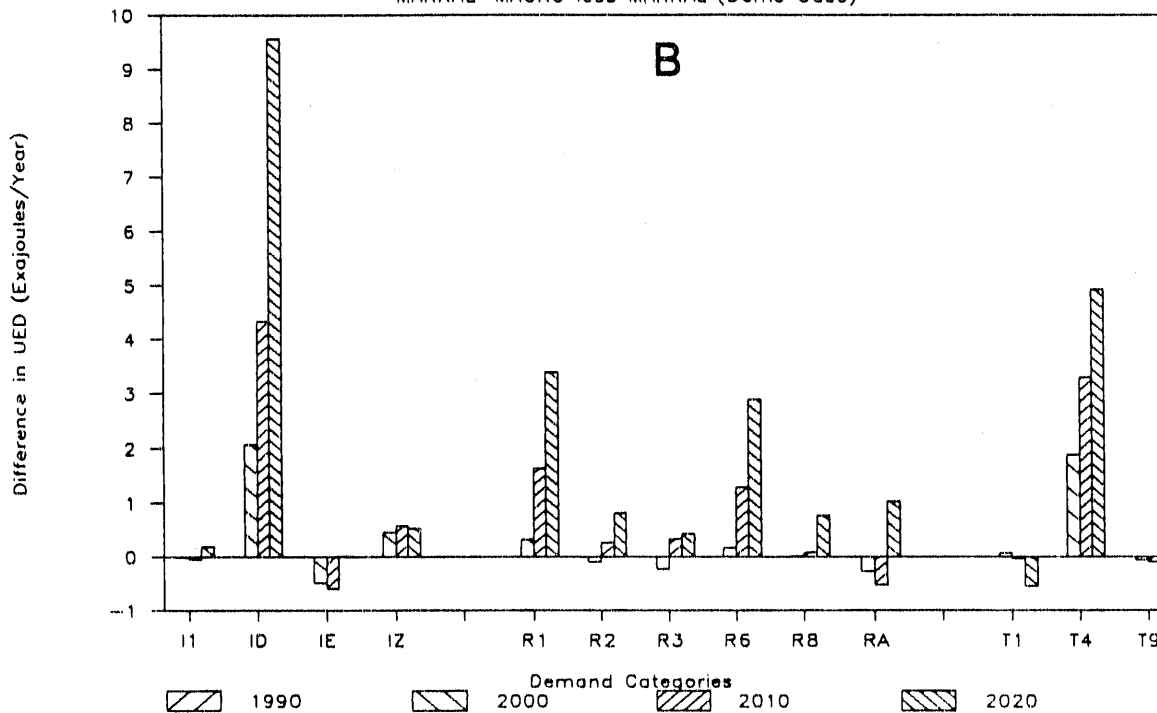


Figure 4-3A,B. Useful Energy Demands - MARKAL-MACRO vs. MARKAL

The top figure shows the results for 1990-2020 from MARKAL-MACRO. The bottom figure shows the differences between the MARKAL-MACRO Useful Energy Demands and the Useful Energy Demands used as inputs to the MARKAL stand alone model. For an explanation of the demand categories, see caption to figure 4-4.

parameters such as the size of the future family and the demand for second homes. The AEEI factor is not intended to replicate the details of these bottom-up approaches. Moreover, it can be difficult to distinguish between price-induced and autonomous conservation. The AEEI is a supplement to the more sophisticated models. It provides a simple method for generating and documenting alternative scenarios, cross-checking the alternative bottom-up models, investigating the consequences of different assumptions on demand saturation and conservation, and providing a global allowance for new sources of demand.

4.1.3 Prices

For 12 out of 13 categories, Figure 4-3A indicates that demands grow more or less smoothly over time. For the remaining one (IZ, "Hydrocarbons for non-energy use"), the demand remains nearly constant between 1990 and 2020.

Figure 4-4 explains several of these results. The marginal costs for IZ increase by 35-50% over each decade, and this in turn reflects a specific view on the international outlook for crude oil prices. According to Figures 4-2A,B,C, these increases are so steep that one would expect transport demands to remain constant. But despite the rising price of crude oil, the marginal cost for end-use item T4 ("Automobile transport") remains constant. It turns out that this can in turn be traced to the MARKAL database in which it is supposed that the market will adopt increasingly more efficient auto transport technologies, and that these will neutralize the increase in oil prices. This leads us to infer that useful energy demand growth for T4 should be close to the production growth factor $A_1(t)$. Figure 4-3A confirms this conjecture.

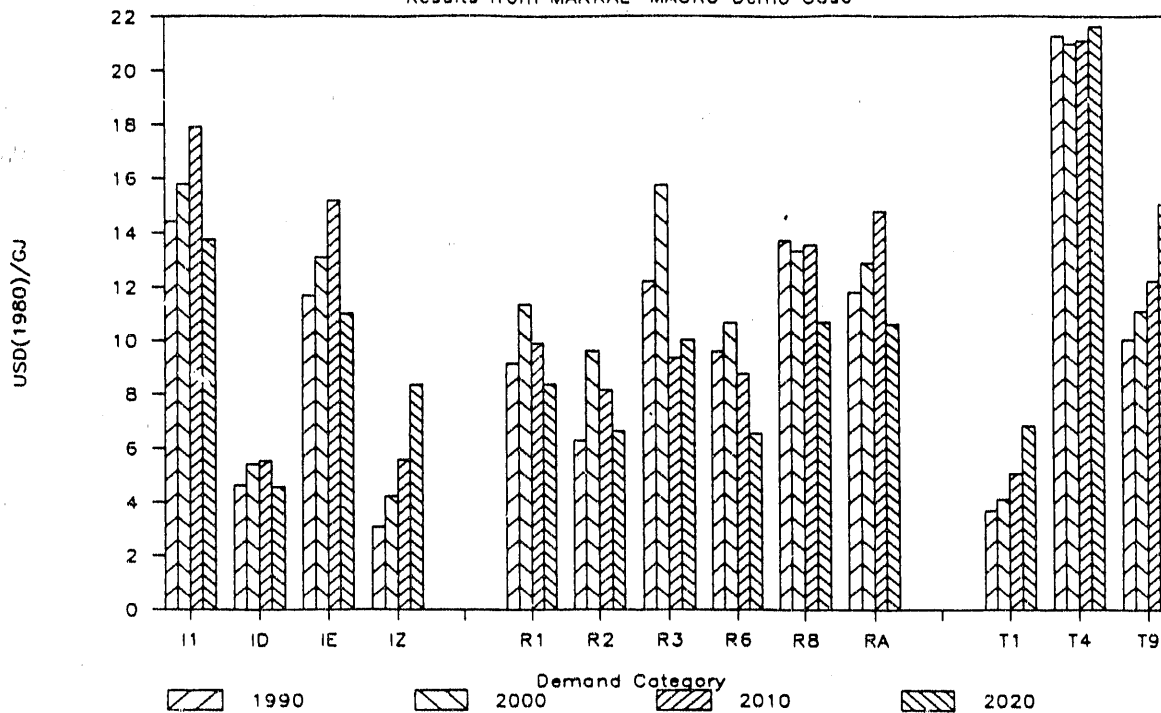
For several demand categories, there is a decline in marginal costs after the year 2000. This is attributable to the emergence of improved or new technologies, e.g. those for space heat and air conditioning.

4.2. Demand technologies and the representation of conservation

The MARKAL model can choose from a menu of demand technologies to supply useful energy demands. For illustrative purposes, Figure 4-5 shows the choices made to satisfy the demand for residential space heat. Both MARKAL-MACRO and the stand-alone MARKAL solutions show that gas will continue to dominate this market. After the turn of the century, there is an improvement in the efficiency of gas heat pumps for space heat and air conditioning. This provides an additional

SHADOW-PRICES FOR DEMANDS

Results from MARKAL-MACRO Demo Case



Demand Category

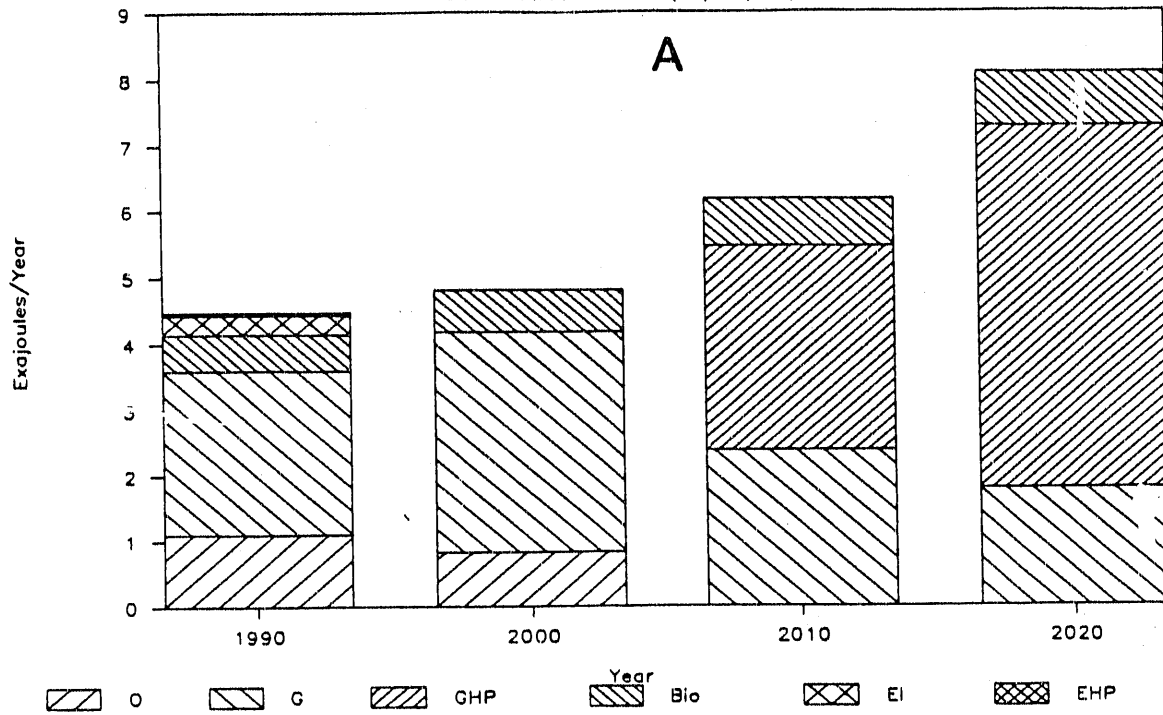
Description

I1	Iron and Steel Metallurgy
ID	Industrial Process Heat
IE	Industrial Electricity
IZ	Hydrocarbons for Non-Energy Use
R1	Residential Space Heat
R2	Residential Hot Water
R3	Residential Air Conditioning
R6	Commercial Space Heat & Hot Water
R8	Commercial Air Conditioning
RA	Residential and Commercial Appliances
T1	Rail/Truck/Bus Transport
T4	Automobile Transport
T9	Air and Ship Transport

Figure 4-4. Shadow prices (marginal costs) 1990-2020 for the 13 demand categories.

Space Heat: MARKAL-MACRO

Demonstration Case (12/03/91)



Space Heat: MARKAL (stand alone)

Demonstration Case

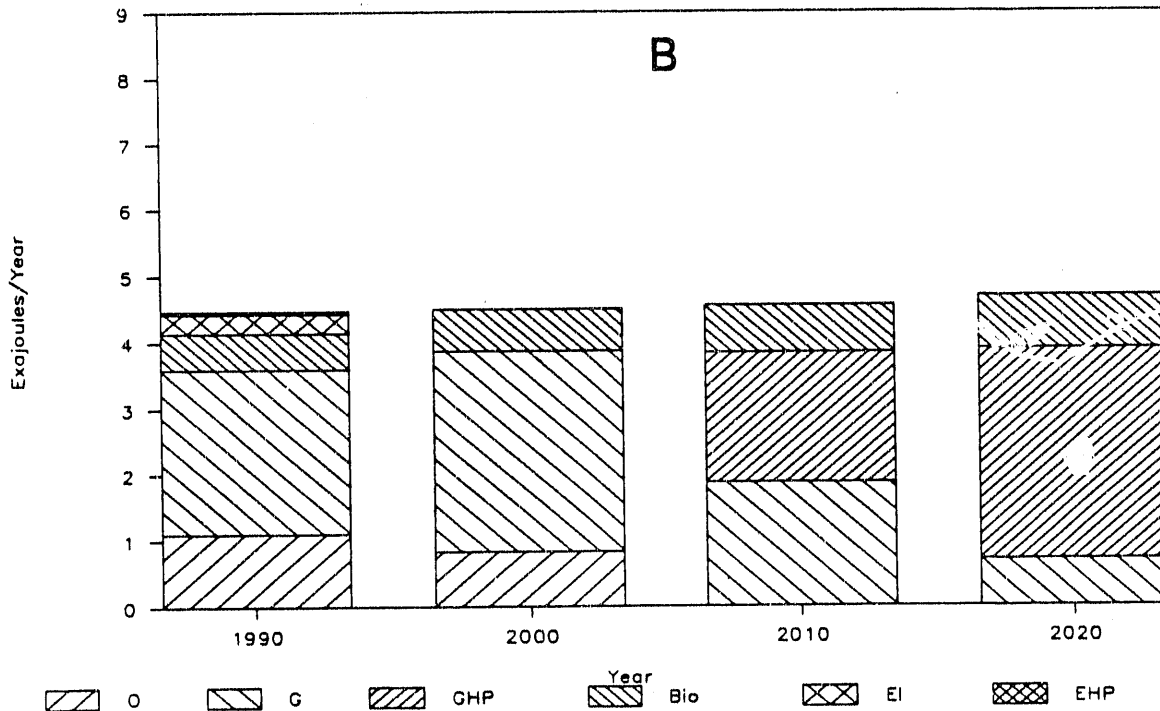


Figure 4-5A,B. Fuels and technologies - residential space heat.

"O": oil burner, "G": gas burner, "GHP": dual purpose gas heat pump - space heat and air conditioning, "Bio": biomass burner, "EI": electric resistance heating, "EHP": dual purpose electric heat pump - space heat and air conditioning.

incentive for the use of gas in the residential market. Oil and electricity are phased out. Biomass is used in rural areas. Most of the differences between the two solutions can be explained by different demand growth rates. The MARKAL demands for residential space heat can be reproduced in MARKAL-MACRO by assuming an AEEI=2.3%. This leads to a large amount of autonomous conservation.

Before proceeding further, it is necessary to specify what is meant by the word "conservation". We propose to restrict this term to denote only those measures that actually reduce the total amount of final energy used to satisfy a given type of demand. The introduction of a renewable technology should not be counted as energy conservation, but rather as the replacement of a fossil or nuclear energy carrier. A heat pump is not a conservation but a substitution technology. It replaces either electricity or fossil fuels by solar energy. There are two reasons for adopting this terminology. First, MARKAL works in an engineering environment where energy balances and the first law of thermodynamics are important concepts for understanding and describing the properties of different technologies. Second, the energy may be renewable but limited in its availability. There will be situations where the available flow of renewable energy is a binding constraint, e.g., in hydroelectric systems where there is a positive shadow price associated with the availability of water during a specific point in the annual cycle of operations.

If we follow these definitions, the MARKAL database has no technical options for price-induced conservation in the demand category "residential space heat", but there are several options for interfuel substitution. These demands can be satisfied by oil, gas, biomass or electricity.

For several demand categories other than residential space heat, the present MARKAL database includes both autonomous conservation and also technical options for price-induced conservation. The following two examples will illustrate how this affects the representation of conservation when we link MARKAL to MACRO.

In MARKAL, conservation can be described as an independent or an associated technology. An independent conservation technology is not tied to any specific form of energy supply. Two examples would be double-pane windows and better insulation. They perform their function independently of the supply technology used for space heating. By contrast, an associated conservation option is an integral part of a supply technology, e.g., more efficient oil burners or automobiles with better mileage.

Figures 4-6 and 4-7 show the technologies selected in MARKAL-MACRO to satisfy the useful energy demands in two categories: industrial electricity and automobile transportation. Independent

Industrial Electricity: MARKAL-MACRO

Demonstration Case (12/03/91)

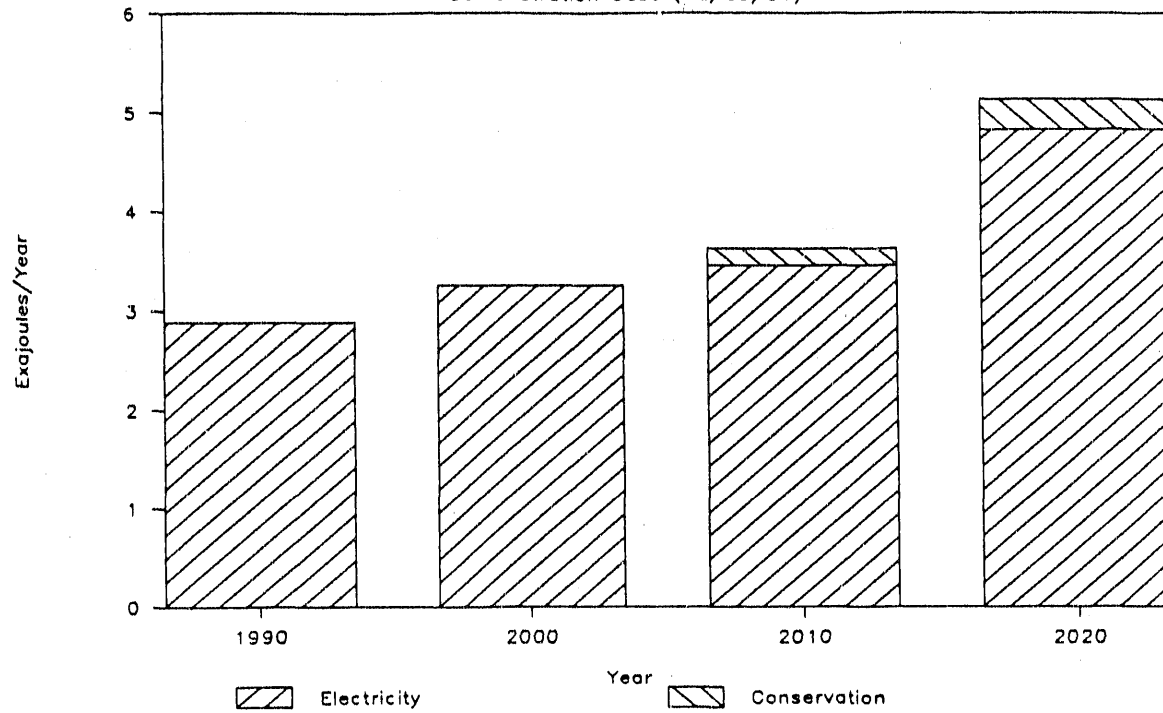
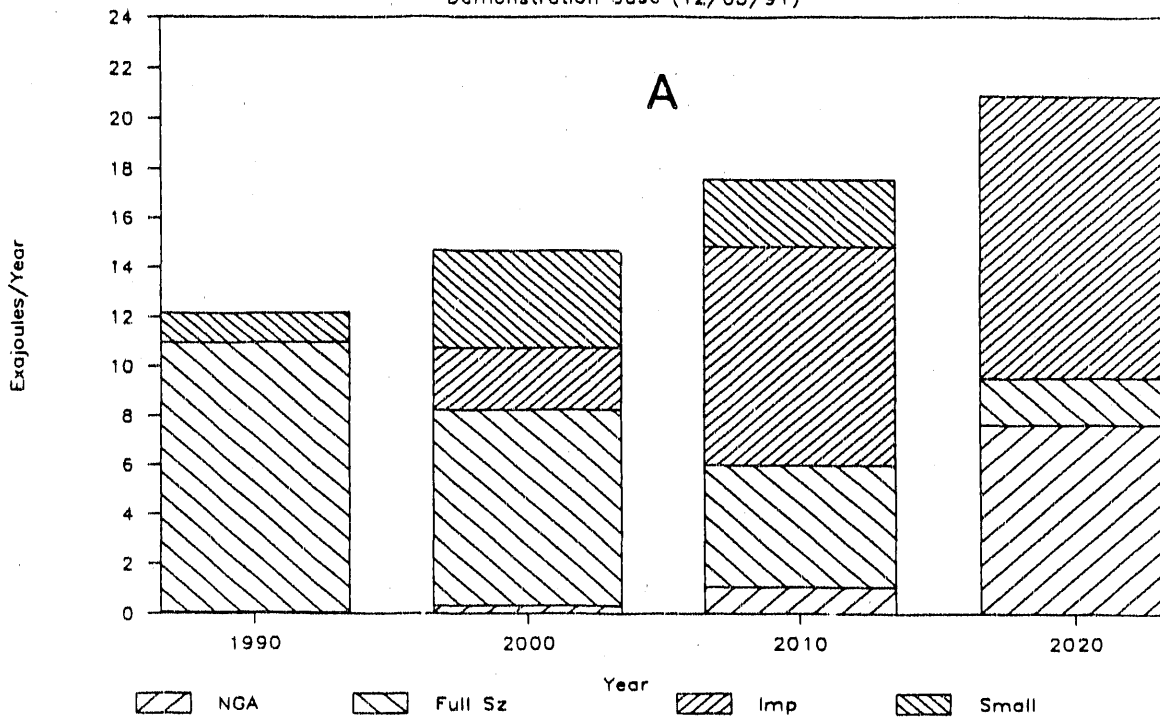


Figure 4-6. Industrial electricity

After year 2000, conservation technologies are implemented to reduce the demand for electricity.

Automobile: MARKAL-MACRO

Demonstration Case (12/03/91)



Automobile: MARKAL (stand alone)

Demonstration Case

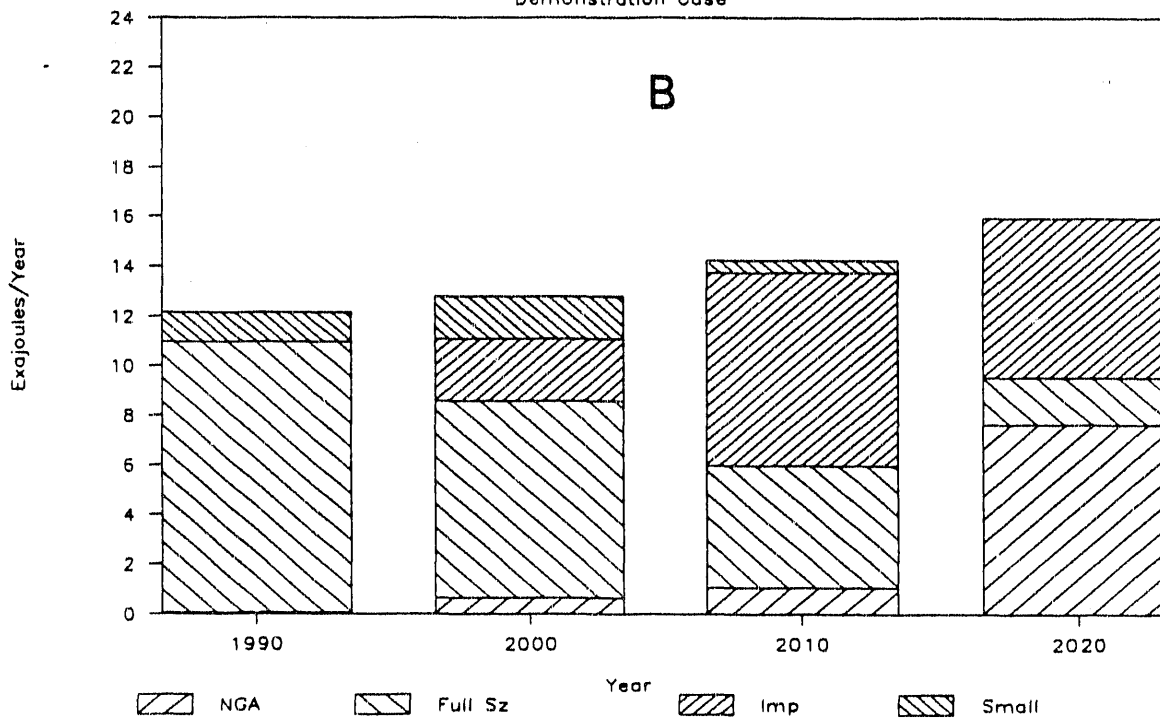


Figure 4-7A,B. Technologies - automobile transportation

"NGA": cars using natural gas, "Full Sz": full size cars using standard otto engines, "Imp": cars with improved otto engines - in 2020, about twice the milage of todays average fleet car, "Small": small cars with otto engines.

and associated conservation measures, respectively, are included in the optimal solutions for these two categories.

For industrial electricity, it is straightforward to show how the electricity conservation technology helps to reduce electricity demands. This is described as a separate technology in the database. It has its own distinct cost and technical attributes. Its effect upon the solution is clearly visible in Figure 4-6.

Automobile transportation is more complicated. By 2020, useful energy demands grow to 20.8 EJ, a 70% increase from the 1990 value of 12.2 EJ. This reflects the growth in services measured in terms of automobile-miles. However, the use of automotive fuels is reduced from 12.2 EJ in 1990 to 11.2 EJ in 2020. Some of this is autonomous conservation associated with the "improved Otto-engine", and some is interfuel substitution associated with the "natural gas engine" technology. Some of these trends are autonomous, and others are price-induced. The information about conservation is available in the database, but is not apparent in Figure 4-7.

MACRO handles conservation from a bird's-eye perspective through the macroeconomic production function. This is a natural way to allow, for example, for the impact of higher gasoline prices upon the average number of miles traveled. All demand categories are treated in a similar way, but there is no technological detail. MARKAL does not treat conservation in this comprehensive way, but the database may be very detailed for specific demand categories. The problem is how to salvage the engineering information from MARKAL for the linked model. We do not want to overlook any option, and we do not want to introduce double-counting by having the same options used both in MARKAL and in MACRO. We intend to explain alternative approaches to this problem.

4.3 Primary Energy

Figures 4-8A and 4-8B compare the primary energy demands from MARKAL-MACRO with those for the comparable MARKAL runs. The composition of fuel use is similar in both cases. Most of the variations may be explained by differences in useful energy demands.

For 2020, MARKAL-MACRO indicates a total that is about 30% higher than MARKAL. In effect, a greater amount of autonomous conservation is built into MARKAL than into the linked model. At the same time, we will have to reconsider the empirical evidence relating to market saturation and other phenomena that affect the AEEI. If this factor were to be, say, tripled from its base value of 0.5% per year, the linked model would lead to results that resemble the stand-alone version of MARKAL.

In the year 2000, 6 EJ more natural gas are used in MARKAL-MACRO than in MARKAL itself. A comparison shows that there is a different time profile for the value of natural gas in the two models. MARKAL-MACRO saves natural gas from low-cost sources for use in the last period. The most likely explanation is that this is a horizon effect. The low-cost sources have a cumulative constraint which limits the total amount of gas, but does not restrict the pattern of extraction from one period to the next. The most likely remedy would be to combine the cumulative constraint with MARKAL's interperiod growth constraint for natural gas.

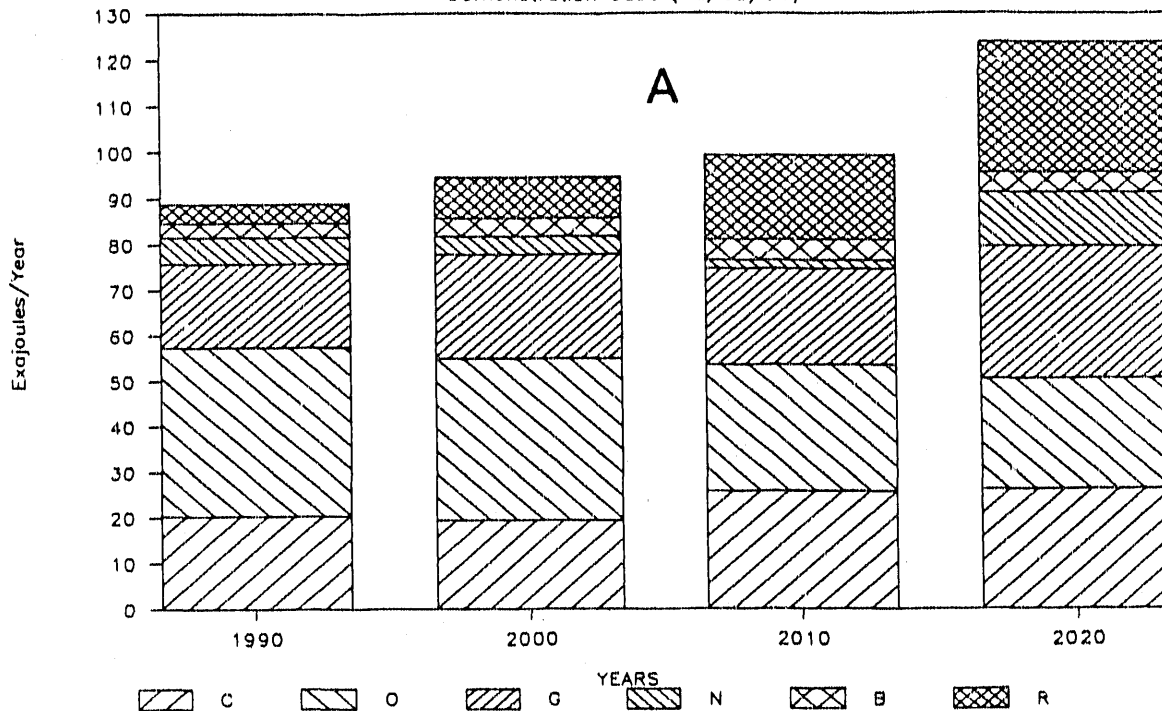
MARKAL invests in new nuclear capacity in 2010, but MARKAL-MACRO waits until the last period. We speculate that this may be due to a horizon effect in the MARKAL stand-alone model. MARKAL includes a salvage credit for long-lived investments such as nuclear reactors, and this may provide an artificial stimulus for early introduction.

Renewable energy provides a significant fraction of the increase in energy consumption, but the total quantity of its use is much the same in the two models. According to the database, these are low-cost technologies, and they tend to be pushed toward their upper bounds. The only exception is solar energy. Photovoltaics do not enter into any of the solutions. This means that solar energy is used exclusively for heating purposes, mainly heat pumps for space heating. The increased used of solar energy in the MARKAL-MACRO solution reflects the increased useful energy demand for space heating.

Carbon dioxide emissions are compared in Figure 4-9. The differences reflect the different use of fossil fuels in the two solutions, and ultimately the differences in useful energy demands. In MARKAL-MACRO, emissions increase slowly from their 1990 value. By contrast, the stand-alone MARKAL shows a monotonic decline of emissions. According to both models, there is a considerable amount of low-cost autonomous conservation available in the automobile sector, and this is the single largest consumer of fossil fuels.

Primary energy: MARKAL-MACRO

Demonstration Case (12/03/91)



Primary energy: MARKAL (stand-alone)

Demonstration Case

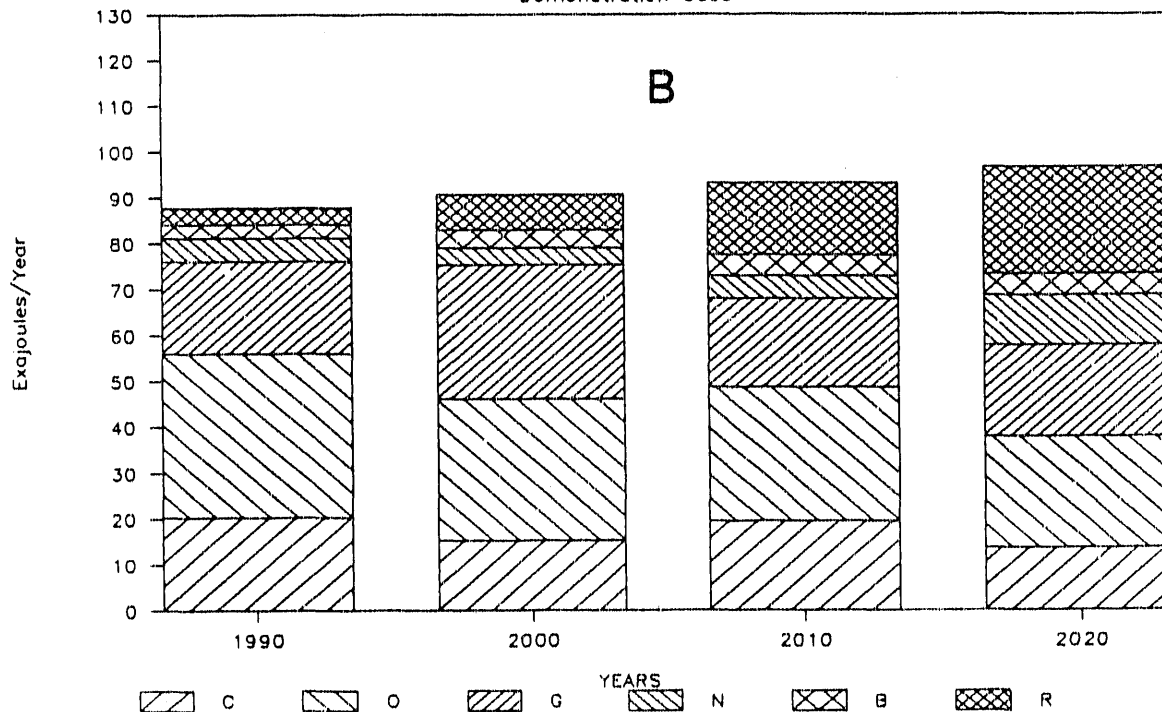


Figure 4-8A,B. Total primary energy demand.

"C": coal, "O": Oil, "G": natural gas, "N": nuclear (fossil equivalent), "B": biomass, "R": other renewables - hydropower, geothermal power, wind power and solar heat (contributions from renewable electric technologies are given in fossil equivalent units).

EMISSIONS OF CARBON DIOXIDE

Comparing MARKAL-MACRO and MARKAL

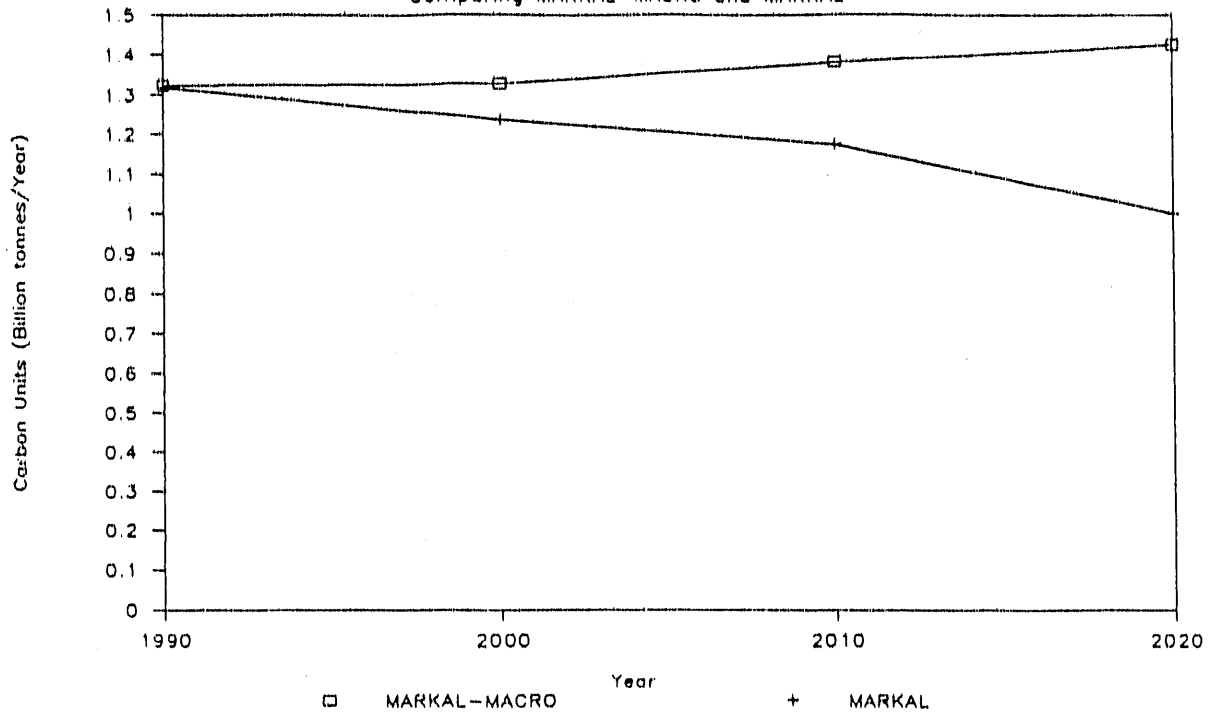


Figure 4-9. Carbon dioxide emissions - comparing MARKAL-MACRO with stand-alone MARKAL.

5. Summary and conclusions

This paper has demonstrated the feasibility of a formal hardlink between MARKAL (a systems engineering model) and MACRO (a long-term macroeconomic growth model). The merger combines MACRO's aggregate view together with MARKAL's detailed analysis of technical options for the energy system.

The differences between the engineer's and the economist's perspectives are highlighted by the current discussion on conservation options and their role in controlling CO₂ emissions. The experience from this demonstration is limited, but it indicates that MARKAL-MACRO provides a tool to facilitate dialogue between the engineer and the economist, and will also facilitate dialogue with policy makers.

Formal linkage ensures consistency between energy supplies, demands and prices, and it imposes a strong discipline upon the model user. We have seen that current MARKAL base year data management practices are incompatible with the benchmarking conditions for prices, quantities and interindustry payments for energy costs. MARKAL-MACRO includes a well-defined relation between demand growth and price changes. This is a prerequisite if we are to distinguish between price-induced and non-price conservation.

In representing conservation within any model, there are two important guiding principles. The description should be inclusive but avoid double counting. Further, the representation should be transparent. It should be easy to communicate whatever assumptions are made about saturation effects or specific conservation technologies. MACRO has a built-in mechanism that ensures transparency. Most MARKAL data bases contain considerable engineering information about conservation, but the information is usually not inclusive. Moreover, because of the richness of technological representations, it may be difficult to convey the meaning of model results to decision makers. In the future, it will be important to develop model procedures that retain the conservation information contained within MARKAL, but avoid double counting when this data base is linked to MACRO.

In addition to revising the treatment of conservation, we have found it necessary to modify the estimate of capacities that remain in place as a result of investment decisions made during and prior to the base year. These estimates of residual capacities will have to be coordinated with an update and with statistical quality control procedures for the data base itself.

Some further developments are necessary to make the model routinely available as a tool for analyzing the U.S. energy system. MARKAL-MACRO is bilingual. The demonstration project has shown that it is possible to translate back and forth between the two languages OMNI and GAMS. It is easy to change specific parameters, but cumbersome to change the model's structure, e.g. to shift from ten-year to five-year time periods. This would involve a fair amount of editing and managing of computer files, and is impractical for widespread use of the linked model. Computer procedures should be developed for converting MARKAL-MACRO into a user-friendly format. These procedures have already been implemented for the stand-alone version of MARKAL, and it should not be difficult to extend them to facilitate the management of inputs and outputs for the linked model.

Appendix A: Model Formulation

Note: MARKAL-MACRO makes use of many of the same ideas as ETA-MACRO. Accordingly, this appendix incorporates some material directly from Manne and Richels (1992).

1. MACRO decision variables and notational conventions

Among the decision variables, the maximand UTILITY is a scalar. All other MACRO variables are time-indexed, and refer to the projection periods $t = 1$ (2000), 2 (2010), 3 (2020). Base year values are denoted by $t = 0$ (1990). For simplicity, the time index t is omitted from the MACRO variables listed below:

UTILITY Sum of discounted logarithms of aggregate consumption

Units of measurement for the following variables are \$ trillions per year (measured in dollars of constant 1980 purchasing power) :

C Consumption
IV Investment
EC Energy costs
Y Production, excluding energy sectors

Units of measurement for the following variables are \$ trillions:

K Capital stock

Units of measurement for the following variables are exajoules (10^{18} joules) per year:

D_{dm} Demand for useful energy type dm - before adjustment for autonomous energy efficiency improvements

Lower bounds are imposed upon almost all of the variables. Some of the lower bounds are zero. Others are positive. These help to reduce the solution time and/or to prevent program calls for undefined numbers, e.g. for the logarithm of zero. The latter class of lower bounds are essential during intermediate iterations, but are intended to be non-binding constraints at an optimal solution.

It may happen that the units of measurement are chosen so that the *logarithm* of consumption is negative. To allow for this unusual possibility, no lower bound is assigned to the UTILITY variable. It is allowed to take on negative as well as nonnegative values.

All decision variables and sets are indicated by upper case letters; all parameters and running indices by lower case letters. The parameters are specified either directly or indirectly through a series of data entries which the user is free to modify. For example, the MACRO.INC file contains the values for gdp_0 (the initial GDP), $kgdp$ (the initial capital-GDP ratio), $kpvs$ (capital's value share), $depr$ (the annual depreciation rate for the aggregate capital stock) and the potential GDP growth rate ($grow$).

2. MARKAL decision variables and constraints

A special-purpose MPS to GAMS conversion program has been written so that all MARKAL variables retain their individual names (as well as their coefficients and bounds) generated by the OMNI-MUSS model generating system. For example, the first column in the MARKAL linear programming matrix is 1EXPCOAC (coal exports during the base year). Within GAMS, this decision variable is identified as $X_{1EXPCOAC}$. That is, the symbol 1EXPCOAC is the first element in the GAMS set J. The generic decision variable is X_j . Similarly, the MARKAL row names are taken over as the elements in the GAMS set I. The input-output coefficient in row i , column j is described as the parameter a_{ij} . The right-hand side constant in row i is rhs_i , and the slack variable in this row is $SLACK_i$.

MARKAL's cost and useful energy demand rows are connected to the MACRO submodel through special-purpose linkage equations. Along with the objective function and the accounting equations of MARKAL, these are described as *non-binding* rows (the GAMS set NBROWS). The other MARKAL equations are *binding* rows (the GAMS set BROWS). All of these binding rows are then incorporated through a single GAMS statement:

$$\sum_{j \in J} a_{ij} X_j + SLACK_i = rhs_i \quad (i \in BROWS)$$

where $SLACK_i$ is fixed at zero if the original MARKAL constraint was an equality. If the original MARKAL constraint was a weak inequality, $SLACK_i$ is either nonpositive or nonnegative depending on the direction of that inequality.

For each variable X_j , the GAMS program calculates a coefficient that describes its impact on the economy-wide energy costs in period t . This parameter is known as $cost_{jt}$. It includes the annually recurring costs that appear in the original MARKAL model. It also includes the annual equivalent amortization payment commitments associated with the investment variables. This is a minor change, but seems necessary if we are to avoid "horizon effects" when we link the two models. MARKAL employs "salvage" coefficients to evaluate the worth of terminal capital stocks. In effect, this is a dual termination condition. By contrast, MACRO employs a primal termination condition.

Following the horizon date, it is supposed that all the MACRO variables will grow at a constant geometric rate.

With these definitions, the following linkage equations determine the impact of the MARKAL variables upon EC_t , the total energy costs in period t :

$$\sum_{j \in J} cost_{jt} X_j = EC_t \quad (t = 1990, \dots, 2020)$$

In MARKAL, there is a fixed demand associated with each form of useful energy during each time period. In the linked model, we treat these demands as decision variables. There is one for each demand type during each time period. Accordingly, these decision variables are known as $D_{dm,t}$. To connect them with the MARKAL supply producing activities, we define the demand correspondence coefficients $dncor_{dm,t,i}$. These coefficients are unity if MARKAL row i is associated with supplying the useful demand category dm during time period t , and are zero otherwise. We may then link the MARKAL supply activities to the MACRO demand variables through the following equations:

$$\sum_{i,j} dncor_{dm,t,i} a_{ij} X_j = aeifac_{dm,t} D_{dm,t}$$

where the coefficients $aeifac_{dm,t}$ allow for any demand reductions associated with autonomous energy efficiency improvements.

To summarize: The *binding* rows are taken over directly from MARKAL. The cost coefficients are recalculated and linked to the macro energy cost variables. The energy supplies are related to the macro demand variables through a zero-one table of demand correspondence coefficients. For further details, see Appendix B. It includes excerpts from the following special-purpose "include" files:

SETS.INC	column set I and row set J (from OMNI-MUSS)
NBROWS.INC	non-binding rows (based on sets.inc) - the complement of the BROWS set
MAT.INC	matrix elements a_{ij} , rhs_j and bounds (from OMNI-MUSS)
COST.INC	GAMS subroutine for calculating the $cost_{jt}$ coefficients from entries in the MAT.INC file
DEMAND.INC	demand correspondence coefficients, reference prices and autonomous energy efficiency improvement rates
MACRO.INC	macroeconomic coefficients

3. MACRO constraints

There is a single equation to define the maximand UTILITY, and there is a single constraint referring to the terminal period, TC. All other constraints are time-indexed. The MACRO constraints are as follows:

UTIL	Discounted utility, sum over all projection periods
USE	Uses of total output - allocated among expenditure categories
PRD	Sources of total output - inputs to production
CAP	Capital accumulation equation
TC	Terminal condition on investment and capital stock

These constraints begin with the UTILITY maximand:

$$\text{UTIL:} \quad \text{UTILITY} = \sum_{t=1}^{T-1} (\text{udf}_t)(\log C_t) + (\text{udf}_T) (\log C_T) / [1 - (1-\text{udr}_T)^{10}] \quad ,$$

where the utility discount rate for period $t = \text{udr}_t = (\text{kpvS}/\text{kgdp}) - \text{depr} - \text{grow}_t$, and the utility discount factor for period $t = \text{udf}_t = \prod_{\tau=0}^{t-1} (1 - \text{udr}_\tau)^{10}$. The exponents of 10 allow for the fact that the first $T-1$ periods are each 10 years in length. The terminal period extends an infinite length of time after period T . This is the reason for the divisor shown in square brackets.

A numerical example shows how the utility discount rate is determined if the following parameter values are adopted:

kpvS	= capital's value share	= 24%
kgdp	= initial capital-GDP ratio	= 2.4 years
depr	= depreciation rate	= 5%/year
$\text{net rate of return on capital}$		= $(24\%/2.4 \text{ years}) - 5\%/year = 5\%/year$
grow_t	= potential growth rate	= 2%/year
$\therefore \text{udr}_t$	= utility discount rate	= 3%/year

The utility discount rate is chosen for *descriptive* rather than normative purposes. With the logarithmic single-period utility function, these values ensure that the optimal steady-state growth rate will coincide with that assumed for the potential GDP. Along an optimal path, the rate of decline in

the present value of the marginal utility of consumption will equal the net marginal productivity of capital. (For a calculus-of-variations proof of this proposition, see Chakravarty (1969, p. 65).) Moreover, these discount rates mean that the economy-wide savings rate will adjust downward (upward) automatically if there is a drop (rise) in the potential GDP growth rate.

The USE equations specify that the gross value of production is to be used for current consumption, investment for building up the stock of capital, and interindustry payments for energy costs:

$$\text{USE}_t: \quad Y_t = C_t + IV_t + EC_t \quad t = 0, \dots, T$$

Since the variable C_t enters only into the objective function and into equation USE_t , the dual variable for this constraint may be interpreted as the present value of the marginal utility of consumption during period t . First-order optimality conditions lead to the Ramsey rule for the optimal allocation over time between savings, investment and consumption. That is, the marginal productivity of capital determines the rate of decline of these dual variables from one period to the next. All other dual variables for period t have a similar interpretation. They are *present* value prices. In order to convert them into *future* values, they must be divided by the dual variables for the USE_t constraints. According to the numerical example cited above, the net marginal productivity of capital is 5%, and the dual variables for the USE_t constraints would decline by about 5% annually.

Aggregate output during period t is determined by a *nested* CES (constant elasticity of substitution) production function. The first term indicates that capital and labor may be substituted directly for each other, e.g. through automation of labor-intensive tasks. The higher the wage rate, the more attractive it becomes to adopt automation. Similarly, the second term indicates that each of the end uses of energy may be substituted for the others. The higher the price of one of these forms, the more attractive it becomes to adopt another - or to engage in price-induced energy conservation through substituting more capital and labor per unit of output. The production function is of the following specific form:

$$\text{PRD}_t: \quad Y_t = [a k l (K_t)^{\rho \alpha} (L_t)^{\rho(1-\alpha)} + \sum_{dm} b_{dm} (D_{dm,t})^{\rho}]^{1/\rho} \quad t = 1, \dots, T$$

At its top level, this nested function has two terms. The first may be interpreted as a value added aggregate of capital and labor based upon a unitary elasticity of substitution. The second is a

separable energy aggregate. In effect, we are making the assumption of "want independence". See Frisch (1959).

The parameter α (also known as *kpsv*) may be interpreted as the optimal value share of capital in the value added aggregate. The exponent ρ is related to ESUB (the elasticity of substitution between the energy and the value added aggregates) through the following equation: $\rho = 1 - (1/\text{ESUB})$. For the concepts and terminology of macroeconomic production functions and neoclassical growth theory, see Allen (1968).

The labor force (measured in "efficiency units") is an exogenously specified index number, L_t . Its values are: $L_0 = 1$, and $L_{t+1} = (1+\text{grow})^{10} L_t$.

Given the values for the two exponents α and ρ , a base year benchmarking procedure is employed to determine the coefficients akl and b_{dm} in the production function. Let $pref_{dm}$ denote the "reference" price of useful energy form dm in the base year. Neglecting the time subscripts for this year, a first-order optimality condition implies that :

$$\partial Y / \partial D_{dm} = (Y / D_{dm})^{1-\rho} b_{dm} = pref_{dm}$$

Except for b_{dm} , each element in the preceding equation is known from the base year statistics or from other input parameters. After solving for b_{dm} , we employ the base year values directly within the production function. The base year labor force index is 1. Since this nested CES production function is based upon constant returns to scale, we may rely upon exhaustion-of-product to solve the following equation directly for the parameter akl :

$$Y^\rho = akl K^{\alpha\rho} + \sum_{dm} b_{dm} (D_{dm,t})^\rho$$

The CAP equations describe the dynamics of capital accumulation. Within each 10-year period, net new capital formation is determined by gross investment less depreciation. Let the annual depreciation rate be indicated by *depr*. Then the ten-year capital survival rate, $tsrv = (1 - depr)^{10}$. Since investment is measured as an annual flow, an accumulation factor of 5 is applied to the beginning and ending rate of investment so as to determine net new capital formation during the decade as a whole:

$$\text{CAP}_{t+1}: K_{t+1} = tsrv K_t + 5 [tsrv I_t + I_{t+1}] \quad t = 0, \dots, T-1,$$

where $I_0 = (\text{grow} + depr)K_0$.

At the end of the planning horizon, a terminal constraint is applied to ensure that the rate of investment is adequate to provide for replacement and net growth of the capital stock during the subsequent periods.

$$\text{TC:} \quad K_T (\text{grow} + \text{depr}) \leq I_T$$

In effect, it is assumed that the MACRO variables will grow at a constant geometric rate during the post-horizon period. This is a primal terminal condition. It reduces "horizon effects", but is not guaranteed to eliminate them entirely. For a more complete discussion of terminal conditions, see Svoronos (1985).

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APPENDIX B. Excerpts from MARKAL-MACRO input files

SETS.INC FILE (from MPS to GAMS conversion program)

SET I /

PRICER
1ANNCOST
3ANNCOST
5ANNCOST
7ANNCOST
1INVEST
3INVEST
5INVEST
7INVEST

.
.
1CPTE01
3CPTE01
5CPTE01
7CPTE01

SET J /

1EXPCOAC
3EXPCOAC
5EXPCOAC
7EXPCOAC

.
.
1E01INV
3E01INV
5E01INV
7E01INV

.
.
1E01CAP
3E01CAP
5E01CAP
7E01CAP

NBROWS.INC FILE (edited from SETS.INC)

NBROWS Non-binding rows - to be eliminated from equality constraints

/PRICER

1ANNCOST
3ANNCOST
5ANNCOST
7ANNCOST
1INVEST
3INVEST
5INVEST
7INVEST

MAT.INC FILE (from MPS to GAMS conversion program)

```

PARAMETER A(I,J);
PARAMETER RHS(I);
PARAMETER OBJ(J);
PARAMETER LB(J);
PARAMETER UB(J);
PARAMETER SLACKLB(I);
PARAMETER SLACKUB(I);
UB(J)=INF;
  SLACKLB('1BALCOA ')= -INF;
  SLACKLB('3BALCOA ')= -INF;
.
  SLACKUB('CUMECOAC')=INF;
  SLACKUB('CUMMCOA1')=INF;
.
OBJ('1EXPCOAC')=      -11.5896;
A('PRICER ','1EXPCOAC')=      -11.5896;
A('1ANNCOST','1EXPCOAC')=      -1.12;
A('NONRENEW','1EXPCOAC')=      -10;
A('1NONRENEW','1EXPCOAC')=      -1;
A('ENVCO2 ','1EXPCOAC')=      -217;
A('1ENVCO2 ','1EXPCOAC')=      -21.7;
A('FOSSIL ','1EXPCOAC')=      -10;
A('1FOSSIL ','1EXPCOAC')=      -1;
A('1BALCOA ','1EXPCOAC')=      -1;
A('CUMECOAC','1EXPCOAC')=      0.01;
.
.
.
OBJ('1E01INV ')=      2057.3659;
A('PRICER ','1E01INV ')=      2057.3659;
A('1INVEST ','1E01INV ')=      1612;
A('1CPTE01 ','1E01INV ')=      -1;
A('3CPTE01 ','1E01INV ')=      -1;
A('5CPTE01 ','1E01INV ')=      -1;
.
.
.
RHS('1CPTE01 ')=      298;
RHS('3CPTE01 ')=      198.6667;
RHS('5CPTE01 ')=      99.3333;
.
.
.
UB('1MINOIL3')=      9699;
UB('3MINOIL3')=      5200;
UB('5MINOIL3')=      4295;
UB('7MINOIL3')=      3390;
.
.
.

```

COST.INC FILE

SET YR USEFUL LIFE - YEARS
/ 10Y, 20Y, 30Y, 80Y/
SCALAR ROR NET RATE OF RETURN PER YEAR - PERCENT /5.0/

TABLE JL(J,*) USEFUL LIVES AND YEAR-BY-YEAR ANNUITY PAYMENT COMMITMENTS

	LIFE	1990	2000	2010	2020
1T1QINV	10	1			
3T1QINV	10		1		
5T1QINV	10			1	
7T1QINV	10				1
.					
.					
.					
1E01INV	30	1	1	1	
3E01INV	30		1	1	1
5E01INV	30			1	1
7E01INV	30				1
.					
.					
.					

PARAMETERS

PV ONE-YEAR PRESENT VALUE FACTOR
CRF(J) CAPITAL RECOVERY FACTOR - INVESTMENT ACTIVITIES;

$$PV = 100/(100+ROR);$$

First payment is made during the same year as capacity becomes available.
Spreadsheet calculation indicates following results for 5% ROR.

LIFE	CRF
10Y	.1233
20Y	.0764
30Y	.0620
80Y	.0486

CRF(J) % JL(J, "LIFE") = (1 - PV) / (1 - PV**(JL(J, "LIFE")));

PARAMETERS

ICOST(J) INITIAL INVESTMENT COSTS

COST(J,TP) ANNUAL EQUIVALENT COST COEFFICIENTS;

* First we calculate the initial investment costs.

ICOST(J) = A("1INVEST",J) + A("3INVEST",J)
+ A("5INVEST",J) + A("7INVEST",J);

* Then we calculate their annualized equivalent.

ICOST(J) = ICOST(J) * CRF(J);

* Now we calculate the year-by-year annualized investment and operating costs.

COST(J,"1990") = ICOST(J)*JL(J, "1990") + A("1ANNCOST",J);
COST(J,"2000") = ICOST(J)*JL(J, "2000") + A("3ANNCOST",J);
COST(J,"2010") = ICOST(J)*JL(J, "2010") + A("5ANNCOST",J);
COST(J,"2020") = ICOST(J)*JL(J, "2020") + A("7ANNCOST",J);

DISPLAY COST;

DEMAND.INC FILE

SET

DM USEFUL ENERGY DEMAND CATEGORIES - MACRO MODEL

/ I1, I0, IE, IZ, R1, R2, R3, R6, R8, RA, T1, T4, T9/

* To avoid reserved word "IF", changed feedstocks identifier to "IZ".

TABLE DDAT(DM,*) DEMAND DATA

	PREF	AEI1
*	\$ per GJ	% per year
I1	10.6	.5
I0	3.0	.5
IE	10.6	.5
IZ	2.8	.5
R1	8.5	.5
R2	6.4	.5
R3	7.4	.5
R6	9.2	.5
R8	7.4	.5
RA	10.6	.5
T1	3.4	.5
T4	21.0	.5
T9	2.5	.5

* PREF obtained from a prior MARKAL run.

TABLE DMCOR(DM,TP,I) - CORRESPONDENCE BETWEEN MACRO AND MARKAL DEMAND NAMES

	1DEM11	3DEM11	5DEM11	7DEM11
I1.1990	1			
I1.2000		1		
I1.2010			1	
I1.2020				1
+	1DEMID	3DEMID	5DEMID	7DEMID
I0.1990	1			
I0.2000		1		
I0.2010			1	
I0.2020				1
.				
.				
.				

PARAMETERS DO(DM) Base year final demands - from MARKAL;

DO(DM) = .001*SUM(I, RHS(I)*DMCOR(DM,"1990",I));

DISPLAY DO;

MACRO.INC FILE

Now we list the macro parameters. Units are as follows:

	MARKAL	MACRO
Energy	petajoules (10**15 J)	exajoules (10**18 J)
Energy prices	\$ per GJ	\$ per GJ
Total costs, 1980 dollars	10**6	10**9

SCALAR GDP0 INITIAL GDP (1980 \$ TRILLIONS);

* To convert from 1990 to 1980 dollars, used implicit GDP deflator,
 * CEA Annual Report, February 1991, p. 290.

GDP0 = 5.463*85.7/131.5;

SCALARS

KQDP INITIAL CAPITAL-GDP RATIO / 2.4 /

GROW ANNUAL PERCENT GROWTH - POTENTIAL GDP / 2.00 /

DEPR ANNUAL PERCENT DEPRECIATION / 5.00 /

KPVS CAPITAL VALUE SHARE PARAMETER / .24 /

ESUB ELASTICITY OF SUBSTITUTION BETWEEN K-L AND E / .5 /

* Change the following parameter if MARKAL base year data are revised.

ECO INITIAL ENERGY COSTS / .430 /

END

**DATE
FILMED**

4 / 28 / 92

