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MARKAL-MACRO: An Overview

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1 Introduction

1.1 Linking energy and economy-wide models

MARKAL-MACRO is an experiment in model linkage. This new tool is intended as an improvement over existing methods for energy policy assessment. It is designed specifically for estimating the costs and analyzing alternative technologies and policies 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 evolution 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 few 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. In order to respond to 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 and an understanding of their nature, 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 will lead to changes in the relative prices of individual energy carriers. If prices rise, there will be price-induced conservation. A major transition would require the reallocation of resources from other parts of the economy. It could affect capital formation and 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. MARKAL and MACRO

Good documentation is available for the individual models MARKAL and 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). In MARKAL-MACRO, these two models are linked formally. Much of this report is drawn from an earlier description of the integrated model by Manne and Wene (1992).

Both submodels 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 - to 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 is supposed that comprehensive supply curves are too difficult to estimate, and price-induced conservation options are 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 several experiments with *informal* linkage to other models. The first work along these lines was reported by Hoffman and Jorgenson (1977). For subsequent work, see Berger et al. (1987) and Yasukawa et al. (1989). We are unaware of previous efforts at "hardlinking" between MARKAL and a long-term macroeconomic growth model.

MACRO takes 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 (i.e., structural trends) 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 thoughout 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. Typically, 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, but it has considerably more technological detail. 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.

MARKAL-MACRO employs the newest U.S. version of MARKAL. Time is analyzed in five-year steps, beginning with 1990 as a base year and extending through a planning horizon of 2030. There are 60 energy supply processes and 48 electric conversion technologies. The model incorporates seasonal and diurnal variations in the demands for electricity and district heating. There are 120 end-use technologies for supplying the 23 categories of useful energy demands. These are viewed as primary inputs into the MACRO production function.

Useful energy demands are exogenous parameters in the stand-alone MARKAL, but are determined endogenously within MARKAL-MACRO. 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. Interfuel substitution and technologically-determined conservation lie 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 ? summarizes some of the technical difficulties that had to be overcome. Section 4 describes the modeling language and users' support system. Section 5 presents typical numerical results.

2. MARKAL, MACRO and the linkage approach

2.1 The basic concepts

Figure 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).

This is an intertemporal rather than a recursive system. Since savings and investment decisions are modeled through the maximization of discounted utility, expectations affect the accumulation of capital over time. Expectations also affect the optimal rate of depletion of exhaustible resources and the speed of introduction of new technologies.

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 has been used for studies of the national energy systems for most countries within the IEA. See Tosato et al. (1984). It has also been used to support energy planning in developing nations such as Brazil, China, Ecuador and Indonesia. It has been 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 include emissions for each activity in which energy is transported or converted from one form to another. MARKAL describes these routes, energy conversion and distribution technologies and various emissions control options. The model identifies those routes and technologies that best satisfy the overall objectives of the energy-environmental 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 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 constraints indicating the cumulative 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.

In a linear programming model such as MARKAL, it is straightforward to impose upper bounds upon the level of a technology in a single period and upon the rate of growth between two periods. These are absolute bounds and cannot be violated. In a *non*linear programming model, one can introduce "soft" bounds — limits that may be violated but at progressively higher costs. Accordingly, we have added a new feature to MARKAL: quadratic penalties for above-normal rates of market penetration. The user specifies a "normal" rate of growth for new technologies, and also specifies the quadratic penalty factor. This allows the model to simulate "crash" programs for rapid but costly rates of market penetration of new technologies. Through the nonlinear formulation, we smooth the introduction rates, and avoid the rapid discontinues that otherwise tend to be observed in linear programming models. The new feature operates independently of MARKAL's absolute limits. These remain available to the user.

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. That is, 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. This is also an indirect way of allowing for behavioral responses such as lowering the thermostat in residential and commercial buildings.

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.

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). In the present version of MARKAL-MACRO, we have not attempted to distinguish between short- and long-run price elasticities of demand. As a result, there can be discontinuities in the demands between the base year of 1990 and the first projection year of 1995. The model is designed for long- rather than short-run analysis.

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 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 Benchmarking the model (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 the useful energy demands enter as inputs into the energy aggregate. Thus, benchmarking involves the estimation of a coefficient for the capital-labor term and for the 23 components in the energy aggregate.

To calibrate the MACRO submodel, the following 1990 base year data are required: GDP, aggregate energy costs, the demand and the "reference" 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.

The calibration procedure gives the modeler some degrees of freedom, but it also requires careful attention to the logical consistency of the base year data. The linked model requires estimates of base year economic activities such as the energy system's total capital charges and operating costs. It also requires an estimate of the investment levels, import costs and export revenues. The GDP is readily available from standard statistical sources. The base year useful energy demands may be taken from the stand-alone version of MARKAL.

The user must be careful in determining the reference prices needed for calibrating the production function. If prices were to remain constant at these levels, energy demands would coincide with the GDP growth rate less the AEEI value. In principle, the reference prices should be identical with the undiscounted marginal costs (also known as shadow prices) taken from the dual solution to the programming model. In practice, however, it is typical for the primal solution to be overdetermined by the requirements for statistical consistency with base year production and consumption estimates. The supply and demand curves are both vertical at this point. (In technical language, the primal solution is said to be "degenerate", and the dual solution is therefore indeterminate.) As a rough-and-ready shortcut, we have therefore employed the *1995* rather than the 1990 shadow prices for benchmarking purposes.

To illustrate this calibration procedure, Table 1 lists the values of the useful energy demands that are employed as exogenous inputs to MARKAL. It indicates the values of these demands in the base year (1990) and in the terminal year (2030). For 1990, the MARKAL-MACRO demands are fixed to coincide with those in MARKAL, but in 2030 the demands may differ because of price-induced substitution and also because of energy-economy feedbacks.

Useful energy demands are *decoupled* from GDP growth by parameters that are termed the AEEI (autonomous energy efficiency improvement) rate. These decoupling factors represent a variety of non-price variables that affect useful energy demands. Examples include: nonunitary income elasticities of consumer demand, saturation phenomena and long-term changes in interindustry composition. There may be new sources of energy demands such as an increase in the quantity of electricity required for electronic computers in the home and office. For example, the analyst needs to have the option of projecting a slowdown in population growth rates, and therefore a decoupling between heating needs and aggregate income growth. At the same time, the growth of air transport may be higher than that of the economy as a whole. The integrated model is designed so that these base (or potential) growth rates are subject to modification as a result of price-induced conservation and energy-economy feedbacks.

To estimate the AEEI decoupling rates empirically, we have tried to be consistent with the useful energy demand projections employed in MARKAL. According to Table 1, the annual MARKAL growth rate for category R0 (residential space heat), is only 0.9% between 1990 and 2030 — even though the GDP growth rate is projected at an average of 2.0%. Accordingly, we take take the AEEI for category R0 to be 2.0 - 0.9 = 1.1%.

For most of the 23 end-uses, this procedure leads to a positive value of the AEEI. There are only three categories (R2, R9 and T4 — residential cooling, commercial miscellaneous appliances and air transport, respectively) where the MARKAL end-use demand growth rate exceeds that of the GDP. In these cases, we impute a *negative* value to the AEEI. This is by no means a satisfactory way to allow for new uses of energy, but it provides a starting-point for a productive dialogue between the advocates of top-down and of bottom-up approaches to energy analysis.

To summarize: The MACRO submodel requires only modest amounts of data in addition to those that are normally required for MARKAL. The additional data requirements include the following: base year GDP; potential GDP growth rates; initial capital-output ratio; aggregate depreciation rate; and the elasticity of substitution between capital-labor and useful energy demands. All other elements of the linked model may be deduced either directly or indirectly from these parameters. E.g., capital's initial value share of the GDP may be determined from the capital-output ratio, the depreciation rate and the net return on capital that is employed in the stand-alone version of MARKAL.

Table 1. Useful energy demand projections employed in MARKAL

Useful energy demand category		1990	2030	annual growth rate, %
		(exajoules)		
R0	Residential space heating	4.04	5.78	0.90
R1	Residential water heating	1.10	1.57	0.90
R2	Residential cooling	1.37	4.13	2.80
R3	Residential lighting and appliances	2.26	4.98	2.00
	Subtotal, residential	8.77	16.47	1.59
R5	Commercial space heating	2.48	4.97	1.75
R6	Commercial water heating	0.12	0.24	1.75
R7	Commercial cooling	2.77	5.54	1.75
R8	Commercial light	1.21	2.42	1.75
R9	Commercial miscellaneous appliances	0.95	2.17	2.10
	Subtotal, commercial	7.53	15.34	1.80
T0	Automobile	8.63	12.86	1.00
T1	Light truck	2.58	3.85	1.00
T2	Heavy truck	5.06	11.18	2.00
T3	Bus	0.14	0.23	1.30
T4	Air	2.73	11.97	3.76
T5	Ship	1.25	2.75	2.00
T6	Rail	0.54	1.20	2.00
TX	Military air	0.58	0.58	0.00
	Subtotal, transport	21.52	44.61	1.84
I1	Iron and steel	0.80	0.80	0.00
IA	Aluminum	0.32	0.70	2.00
ID	Industrial boilers	4.39	9.69	2.00
IE	Fabrication and electric drive	2.51	5.54	2.00
IH	Other industrial heat	4.82	10.67	2.00
	Subtotal, industrial	12.84	27.38	1.91
NY	Non-energy demands	1.15	2.54	2.00
	Total useful energy demands	51.81	106.34	1.81

3.2 Treatment of capital charges and residual capacities

In earlier applications, the MARKAL and MACRO submodels differed in their terminal conditions and in their treatment of capital charges. MARKAL views investments as one-time expenditures that provide a stream of capacities available during subsequent time periods. If a capital investment survives past the horizon date, it receives 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. That is, the rate of investment in the final period must be large enough to allow post-horizon growth to proceed at a constant geometric rate. MACRO allows for investment costs through capital recovery factors — with a uniform annual amortization charge throughout the useful life of plant and equipment. No salvage values are assigned to the stocks of oil, gas, plutonium and other resources available for use during the post-terminal period. 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 both provide for the durability of capital goods, but each in a somewhat different way. 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.

In the stand-alone version of MARKAL, there is no reason to impute capital charges to "residual" capacities (i.e., those remaining from pre-1990 investment activities). For purposes of the linked model, however, it is essential to provide consistent year-to-year accounting for the energy sector's capital and operating costs. We therefore apply capital recovery charges to these residual capacities — just as in the case of new facilities.

3.3 Full vs. differential costing

The stand-alone version of MARKAL is demand-driven. The useful energy demands are provided as inputs. In the linked model, useful energy supplies, demands and prices are interdependent. They are determined jointly by MARKAL and MACRO. Aggregate energy costs (hereafter abbreviated EC) are generated in MARKAL. Along with aggregate consumption and investment, the EC variable represents claims upon the gross output generated by the MACRO production function. EC includes the capital charges, operation and maintenance, and fuel costs for all supply and conversion technologies.

One must be careful in defining the remaining energy costs reflecting end-use demands. Clearly, all fuel costs are included in EC, but not all capital and operating costs. The "final" users of energy (both consumers and producers) consume energy as part of a larger end-use. Gasoline is used to provide transportation. Fuel oil, natural gas and electricity are purchased to provide space heat as part of a comfortable building environment. Boiler fuels for process heat and electricity for electric drives are used as an input in the production of industrial products and services. However, the capital costs of automobiles, highways and other transportation infrastructure are *not* normally viewed as energy sector costs. Similarly, the energy sector does not include the land, buildings, furniture and equipment for buildings. It does not include the general facilities and equipment employed in the manufacturing sector. Outside the energy sector, MARKAL includes only the additional expenditures required for unconventional alternatives. It includes the incremental costs of CNG vs. gasoline-fueled vehicles; of oil vs. resistance heat vs. heat pumps for space heat; of process heat from cogeneration vs. direct generation of process heat for manufacturing. In each of these cases, MARKAL excludes the capital, operating and maintenance costs for a baseline technology, and includes only the additional costs required for the unconventional alternatives.

This convention is consistent with the view that MARKAL is primarily an energy sector model. An alternative device is chosen whenever a useful energy demand can be met at a lower cost by that device than by the existing technology. If the *total cost* of providing end-use services were included in the definition of energy costs, virtually the entire GNP would be attributed to the energy sector. By defining EC to include only the differential costs, we focus upon the fuel component. In choosing between alternative technologies, it is the cost *difference* that determines the winner, not the absolute cost level of the baseline technology. If we had included the absolute levels of all end-use costs, we would have extended MARKAL far beyond the conventional boundaries of the energy sector, and would have distorted the feedback relationships with the MACRO portion of the combined model.

Even if the definition of EC had been constrained to include only automobiles and energy-using equipment, there would have been a disproportionate impact upon the non-energy sectors of the economy.

4. Promoting model usability

4.1 GAMS and MUSS

To incorporate nonlinearities in the constraints and objective function, MARKAL-MACRO is written in GAMS (a generalized algebraic modeling system). See Brooke et al. (1988). Data-base management and scenario comparisons are handled through a user-friendly interface known as MUSS (MARKAL Users Support System). See Goldstein (1991). Through MUSS, the user can modify the individual MARKAL tables provided in their traditional OMNI format. The interface then translates these tables into a form that can be recognized by GAMS. It also handles the additional data required for the MACRO submodel and for the quadratic penalties associated with rapid rates of market penetration.

4.2 Modeling language and optimizer (GAMS/MINOS)

GAMS is a computer language specifically designed to facilitate the development of algebraic models. The syntax closely resembles the row-oriented style of formulating constraint equations. The MARKAL-MACRO source code is written in GAMS, but has been organized so that MACRO is largely isolated from the MARKAL submodel. This facilitates revisions in model structure.

GAMS provides a convenient interface to nonlinear optimizers, including MINOS (a model in-core nonlinear optimization system). MINOS handles nonlinear objective functions and nonlinear constraints. These are parsed by GAMS so that the user does not need to write down the gradients associated with the objective function and constraints.

With the U.S. MARKAL-MACRO data set analyzed in this report (4500 constraint rows), we come close to the practical limits of the 1992 family of personal computers. On a 486/50-PC, it can take three and a half hours for a "cold start", but restarts typically require only 30-45 minutes.

Each version of the model is controlled by data provided to GAMS in the form of SETs and PARAMETERs. For MARKAL-MACRO, the SETs characterize the energy system by identifying the demand devices, energy carriers, etc. The PARAMETERs (often tables) provide specific information on individual fuels and technologies, e.g. the unit costs, conversion efficiencies and market penetration limits. An important feature of GAMS is its domain checking capabilities. These ensure that all the elements of PARAMETERs and TABLEs fall within the scope defined by the source code's declarations. This helps to identify errors in the input data, e.g. a fuel input to a nonexistent technology.

4.3 Model users' support system (MUSS)

With any large and complex model, it is essential to provide the policy analyst with a model environment shell. Numerous runs must be made under a variety of technical and economic assumptions. Database handling errors are inevitable, but they can be reduced to a minimum if we employ a systematic approach. As shown in Figure 2, MARKAL-MACRO is part of an integrated modeling system that encompasses the models, optimizers, scenario and data management, problem restart handling, sensitivity analysis, and comparative analysis of results through color graphics.

The heart of this environment shell is MUSS. It is a system incorporating the features of a relational database, spreadsheet, file manager, and graphics presentation system. (See Figure 3.) MUSS enhances the productivity of the policy analyst. It enables the user to employ the identical database, and to switch between the original OMNI version of MARKAL, the GAMS version of MARKAL and the GAMS version of MARKAL-MACRO. At some future date, it is possible that there will be an OMNI version of MARKAL-MACRO.

MUSS employs pop-up menus, online context-sensitive help, pick lists and browse capability. These facilitate the location and modification of all numerical input data. The system also provides copy/delete macro commands to assist with standard adjustments to the database, e.g. adding/removing a technology. In the absence of this type of shell, any modification entails a series of error-prone data entry steps. MUSS also includes a Reference Energy System drawing capability.

Data are managed by scenarios. Typically, a reference case is developed and then a series of sensitivity analyses, e.g. alternative rates of market penetration for renewable technologies. For each of these scenarios, alternative cases may be run, e.g. examining the effect of imposing alternative CO2 reduction limits. The user assigns specific names to these scenarios/cases. These determine the names of the files passed to/from MARKAL-MACRO, and they control the access of MUSS to the input data and results. Throughout, the user is provided with dynamic feedback into the data "dictionary". In this way, there is immediate access to the name and characteristics of each technology in each time period.

MUSS provides a convenient way to analyze model results. It facilitates the retrieval of a desired subset of results, and compares the information obtained from alternative cases. The results are organized into tables which are automatically ordered so as provide side-by-side comparison of a single result, e.g., the capacity of light water nuclear reactors, over a set of cases.

Graphs are generated through menus. The analyst places the cursor a a desired line and presses a single key. When examining a single technology, for example, both the capacity level and the associated "reduced costs" can be displayed on a single diagram. This provides an indication of economic attractiveness. Another standard plotting option allows for the display of activity levels of up to 50 technologies from multiple cases for a single year.

In addition to managing the interpretation of model results, MUSS allows the user to combine and reorganize information into custom graph tables. The results may be graphed as bar charts, cumulative bar charts, percentage (pie) charts, etc. Figures 4 - 21 were generated by MUSS.

5. Model results

5.1 Three scenarios

To exercise MARKAL-MACRO, three alternatives were defined: a base case and two carbon emission control scenarios. The *base case* is intended as an extrapolation of current practices and policies. It is one in which we are cautious on the prospects for the introduction of new supply and conservation technologies into the market place. This should not be confused with an "economic potential" scenario — one that indicates what could happen if each cost-effective supply and conservation technology were pushed to its limits. To the extent that MARKAL overstates the performance of any of the new technologies — or understates the barriers to their implementation — such a scenario would have built-in tendencies toward over-optimism.

The second scenario is one in which there is a *deferred* CO2 emissions constraint. Controls are deferred until 2010. From that point onward, emissions are reduced to a level 20% lower than they were in 1990. This type of scenario is broadly consistent with the consensus position of 48 countries participating in the Toronto Conference of June 1988. According to Abrahamson (1989), the goal was described as a 20% reduction in CO2 emissions by 2005. Our scenario defers the initiation of controls by five years. This provides a period for adjustment so that newer and less expensive control options may be adopted. The implementation delay also allows the participating countries more time to reach agreement as to appropriate participatory roles.

The third scenario is one in which there is a *cumulative* CO2 emissions constraint. It is designed to avoid the potentially disruptive effects of imposing controls abruptly in 2010. This scenario accepts the same overall goals as the deferred constraint case. Cumulative emissions are reduced by the same total quantity as in the deferred case. Annual emissions in 2030 are limited to the identical quantity. The impact on global climate would be virtually indistinguishable. With this scenario, there is the flexibility to introduce emission control technologies at either an earlier or a later date than 2010, and this flexibility helps to reduce GDP losses.

It is assumed that the international crude oil price is identical in all three scenarios. The price was $20 per barrel in 1990. Thereafter, as a result of the exhaustion of domestic and international resources, the price rises gradually. It follows a "surprise-free" path, reaching $31 per barrel in 2010 and $44 in 2030. Given this oil price perspective, there is a built-in incentive for conservation and for the development of unconventional energy resources.

5.2 Impact on the energy system

Figure 4 shows the composition of primary energy consumption in the base case. Total primary energy use increases throughout the 40-year planning horizon at the annual rate of 1.12%. Each of the fossil fuels grows less rapidly than the total — coal at an even slower rate than oil and gas. Nuclear energy declines through 2015, but rises quite rapidly thereafter. The contribution of renewables rises continuously. For the period as a whole, its compound annual growth rate is 3.14%.

Figure 5 compares all three scenarios with respect to the composition of energy consumption. In both CO2 control scenarios, there is a massive amount of price-induced conservation. In 2030, the total is 20% lower than in the base case. In the *deferred* case, consumption rises slightly before 2010, shows an absolute decline in that year, but growth is resumed thereafter. In the *cumulative* case, there is a decline in 1995, but a gradual rise thereafter. The 1995 decline should not be taken too literally. This is a direct effect of the failure to distinguish between short- and long-run price elasticities of demand. Had this distinction been introduced into the model, it is likely that there would have been even greater gains from the cumulative rather than the deferred scenario for emission controls.

By contrast with the base case, coal use drops sharply under both CO2 control scenarios. It falls at an erratic rate in the deferred case, but smoothly when the constraints are cumulative. During the early decades, oil is the "swing fuel". In the base case, oil consumption increases steadily. By contrast, in the deferred case, oil use increases slightly until 2005, drops sharply in 2010, and increases thereafter. With the cumulative constraint, oil consumption drops in 1995, and it increases gradually thereafter. Natural gas, nuclear and renewable energy consumption are almost identical across all scenarios in all time periods. Their values are determined largely by exogenous upper bounds.

The useful energy demands (UED) are of particular interest. These are determined endogenously through the interaction of the MARKAL and the MACRO submodels. They are directly affected by price-induced conservation. Figure 6 compares total useful energy demands across all sectors of the economy. Under both emissions control scenarios, demands are lower than in the base case. By 2030, there is an 18% overall reduction. Although the end result is similar, the path toward this reduction differs considerably. Energy consumption rises smoothly with the cumulative CO2 constraint, but it follows a zig-zag path in order to accommodate the year-by-year CO2 requirements of the deferred case. There is a sharp drop between 2005 and 2010, and this leads to significant costs of adjustment. Figure 6 shows the importance of a long-term perspective. By starting early toward a given goal, we follow smooth paths. This contrasts sharply with the disruptive effect of waiting until 2010 to impose controls.

Through a close comparison of Figures 5 and 6, we can see that there is more rapid growth of UED than of total primary energy consumption. As a fraction of primary energy inputs, the UED were 57% in 1990. By 2030, the fraction increases to 77% in the base case and to 80% in both of the CO_2 control scenarios.

Energy intensities are compared in Figures 7 and 8. All three scenarios are characterized by reductions in the overall energy-GDP ratio throughout the planning horizon. This generalization holds both for primary consumption and for the UED. Price-induced conservation leads to greater reductions in the control scenarios than in the base case. The emission reduction goals are achieved partly through switching away from fossil toward carbon-free fuels, and partly by using less energy to satisfy the end use demands.

Figure 9 indicates the overall contributions of electricity to the energy system. In all three scenarios, electricity rises at a slower rate than the GDP. Over the 40-year horizon, it grows 1.43% annually in the base case and .85% when constraints are imposed on CO_2 emissions. Figure 10 compares the sources of electricity generation in 2030. The sharp reduction in coal-fired electricity generation accounts for virtually all of the difference between the base and the control scenarios.

5.3 Impact on carbon emissions

Carbon emissions are compared in Figure 11. There are large differences between the base case and the two control scenarios. In part, these can be traced to price-induced conservation and in part to changes in the fuel mix. According to the base case, emissions will increase throughout the planning horizon. They are 20% higher in 2030 than in 1990. By contrast, both control scenarios end up with a 20% reduction from the 1990 level. Carbon emissions are closely correlated with total primary energy consumption and with UED. There is a smooth path in the base case and in the cumulative scenario. With the deferred scenario, there is an abrupt reduction between 2005 and 2010.

5.4 Impact on the economy

The macroeconomic variables (GDP, investment, consumption and energy costs) are all lower under the constrained scenarios than in the base case. Of the four, total energy supply costs are the most sensitive to the differences between the control scenarios and the base case. (See Figure 12). Figures 13-16 express the differences in terms of dollar costs. By 2030, the cost of imposing CO_2 constraints amounts to a GDP loss of $210-220 billions. The differences appear large when expressed in absolute dollar amounts, smaller when expressed as a percentage of GDP, and still smaller when expressed in terms of differences in growth rates. At first glance, this appears paradoxical, but there is

Table 2

Annual percentage growth rates, 1990-2030

Macroeconomic indicator	Base case	Constrained cases	Reduction
GDP	2.07	2.03	0.04
Consumption	2.10	2.07	0.02
Investment	1.92	1.78	0.14
Energy costs	1.69	1.22	0.47

a ready explanation. The energy sector represents only about 10% of the economy as a whole. When GDP is the divisor, virtually any sectoral magnitude appears small. Moreover, the energy-economy feedbacks are not large enough to lead to major differences in growth rates. See Table 2.

MARKAL-MACRO generates the energy prices required so as to equilibrate useful energy demands with the least-cost mix of available supply technologies. There is one such price for each of the 23 useful energy demands in each year. Figures 17-20 provide typical price series. These refer, respectively, to the residential, commercial, transportation and industrial sectors. Although the year-to-year percentage changes are not identical, the pattern is similar. Base case energy prices rise moderately throughout the time horizon. These trends are a direct consequence of assuming a systematic increase in international oil prices. Higher cost technologies are then needed in order to meet the increases in energy demands.

Under the two control scenarios, prices rise much more rapidly than in the base case. This provides an additional incentive for price-induced conservation. Prices follow the patterns that are characteristic of the three scenarios. The paths are smooth in the base case and in the cumulative control scenario. They exhibit an abrupt increase when controls are deferred until 2010. From that date onward, the prices in both control scenarios converge toward similar values in 2030.

Figure 21 shows the shadow prices (implicit values) of the carbon emission constraints. These represent the incremental cost of further reductions in CO2 emissions. If all reductions are to be achieved through the taxation of carbon, these can be interpreted as the year-by-year tax level required in order to meet the emissions targets. With the deferred controls scenario, prices remain zero through 2005 and then rise sharply in 2010. With the cumulative constraint, there is a positive value in 1995, and the price rises gradually over time. The compound annual growth rate is consistent with the marginal productivity of capital throughout the economy — about 5% annually. In both control scenarios, the price reaches $270 in 2030. In this version of MARKAL, there are no "backstop" technologies — and therefore no upper bound on the price of carbon.

Caveat: Most of these economic impacts may be interpreted as the direct consequences of the input assumptions with respect to supplies, demands and emissions control scenarios. If we are sure that we will eventually have to impose emissions controls, it is preferable to start early, and to adopt a smooth transition strategy. With *certainty* on the imposition of controls, the cumulative case is clearly preferable to the deferred case. With uncertainty, however, it may be preferable to adopt a hedging strategy based upon an explicitly probabilistic decision analysis framework. These three scenarios represent a useful beginning in that direction, but do not in themselves determine an optimal hedging strategy.

6. A concluding note

The three scenarios are not sufficient to validate MARKAL-MACRO, but they do indicate that the model exhibits plausible behavior. By contrast with a stand-alone engineering model, useful energy demands are reduced in response to higher energy prices. Carbon emission constraints lead to lower GDP, investment, consumption and energy supply costs. The quantities and timing can be compared for different policy options, and the price structure indicates the stresses that might be entailed by the imposition of CO2 controls. It is particularly useful to be able to identify those strategies that might lead to smooth rather than difficult transitions.

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.

References

D.E. Abrahamson, 1989. "The Changing Atmosphere: Implications for Global Security", Toronto Conference Statement, June 1988, in *The Challenge of Global Warming*, Island Press, Washington, D.C..

S.J. Ahn, 1992. "MARKAL-MACRO/2 - An Energy-Environmental Modeling System", engineer's thesis, Department of Operations Research, Stanford University.

R.G.D. Allen, 1968. *Macroeconomic Theory*. Macmillan, New York.

C. Berger, A. Haurie, G. Savard, R. Loulou, G. Lafrance and J.-P. Surprenant, 1987. "MEDEQ-MARKAL: Un Couplage Entre Deux Modeles Techno-economiques du Systeme Energetique du Quebec" R.A.I.R.O. *Recherche Operationelle*, Vol.21, No 1.

A. Brooke, D. Kendrick and A. Meeraus, 1988. *GAMS: A User's Guide*, Scientific Press, Redwood City, California.

S. Chakravarty, 1969. *Capital and Development Planning*, MIT Press, Cambridge.

R. Frisch, 1959. "A Complete Scheme for Computing All Direct and Cross Demand Elasticities in a Model with Many Sectors", *Econometrica*, 27.

L.G. Fishbone, G. Giesen, G. Goldstein, H.A. Hymmen, K.J. Stocks, H. Vos, D. Wilde, R. Zolcher, C. Balzer, and H. Abilock, 1983. "User's Guide for MARKAL (BNL/KFA Version 2.0)", BNL 51701, Brookhaven National Laboratory, Upton, N.Y.11973 and Forschungsanlage KFA-Julich, D-5170 Julich.

G.A Goldstein, 1991. "PC-MARKAL and the MARKAL Users Support System - User's Guide", BNL-46319, Brookhaven National Laboratory, Upton, N.Y. 11973.

K.C. Hoffman and D.W. Jorgenson, 1977. "Economic and Technological Models for the Evaluation of Energy Policies", *The Bell Journal of Economics*, vol. 8, no. 12.

J. Johnsson, O. Bjorkquist, C.-O. Wene, 1992. "Integrated Energy-Emissions Control Planning in the Community of Uppsala", *International Journal of Energy Research*.

A.S. Manne and R.G. Richels, 1992. *Buying Greenhouse Insurance: the Economic Costs of Carbon Dioxide Emission Limits*, MIT Press, Cambridge.

A.S. Manne and C.-O. Wene, 1992. "MARKAL-MACRO: A Linked model for Energy-Economy Analysis", Brookhaven National Laboratory, BNL-47161.

W. Marcuse, L. Bodin, E. Cherniavsky, and Y. Sanborn, 1976. " Dynamic Time Dependent Model for the Analysis of Alternative Energy Policies" in: K.B. Haley (editor), *Operational Research '75*, North Holland, Amsterdam.

M.D. Rowe and D. Hill (eds), 1989. "Estimating National Costs of Controlling Emissions from the Energy System, A Report of the Energy Technology Systems Analysis Project, International Energy Agency", BNL 52253, Brookhaven National Laboratory, Upton, NY 11973.

A. Svoronos, 1985. *Duality Theory and Finite Horizon Approximations for Discrete Time Infinite Horizon Convex Programs*, Department of Operations Research, Stanford University, April.

G. Tosato, J. Brady, P. Essam, M. Finnis, G. Giesen, S. Rath-Nagel, H. Vos and D. Wilde, 1984. *Energy After the Eighties, A Cooperative Study by the Countries of the IEA*, Elsevier, Amsterdam.

C.-O. Wene, 1980. "The Optimum Mix of Conservation and Substitution: An example from Retrofitting Old Buildings", *International Journal of Energy Research*, Vol 4.

C.-O. Wene, 1989. "Using a Comprehensive Model for Community Energy Planning", in: L. Lundqvist, L.-G.Mattsson and E.A.Eriksson (eds.) *Spatial Energy Analysis - Models for Strategic Decisions in an Urban and Regional Context*, Avebury, Aldershot.

S. Yasukawa, O. Sato, Y. Tadokoro, T. Nagano, H. Shiraki, T. Kajiyama, Y. Nakano, and Y. Shimoyamada, 1989. "Emission Control Analysis Using the MARKAL Model of the National Energy System of Japan - Part II", in: M.D. Rowe and D. Hill (*op. cit.*).

Figure 1

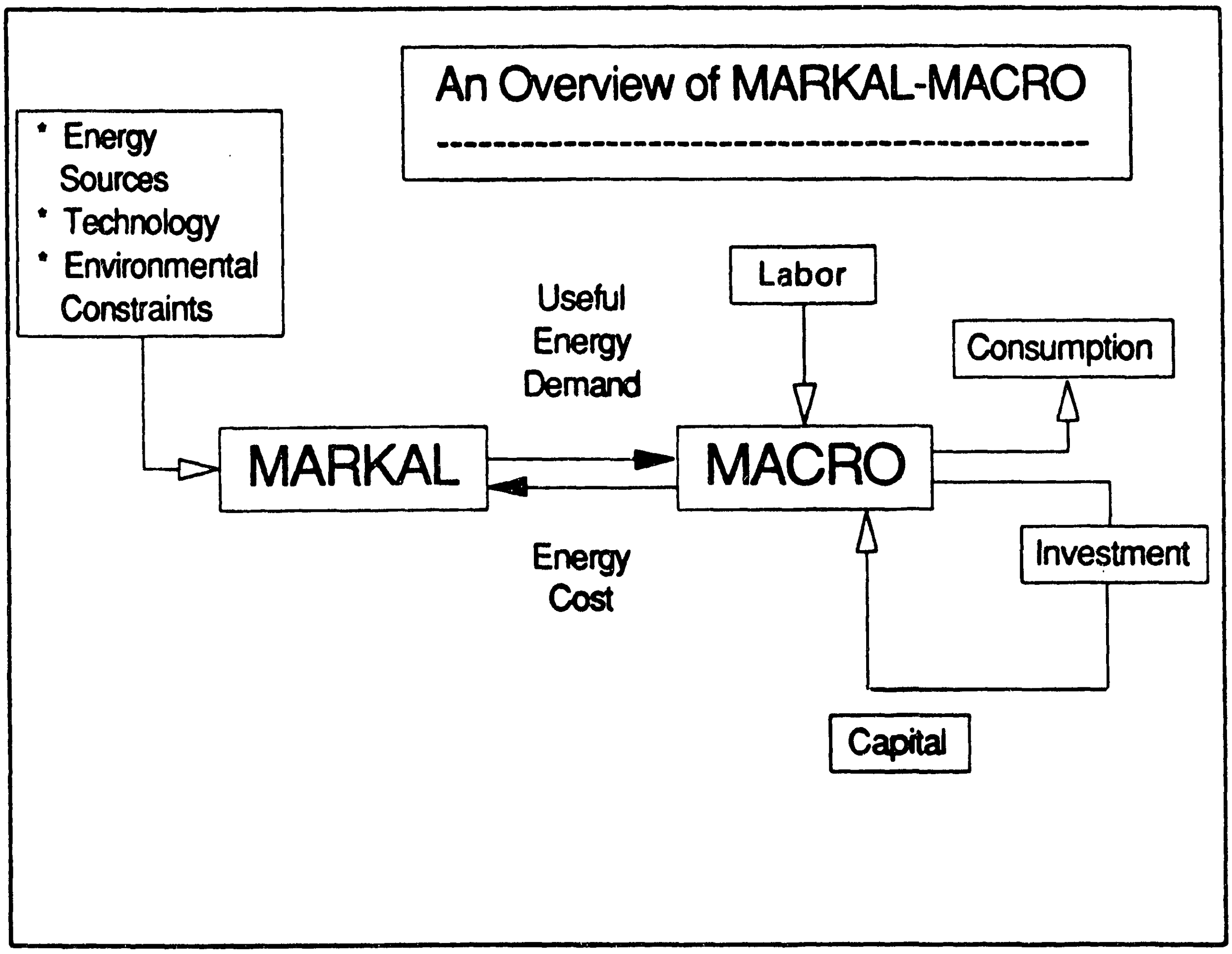

An Overview of MARKAL-MACRO
* Energy Sources
* Technology
* Environmental Constraints
MARKAL
Useful Energy Demand
Energy Cost
MACRO
Labor
Consumption
Investment
Capital

Figure 2

MARKAL/MARKAL-MACRO USERS SUPPORT SYSTEM

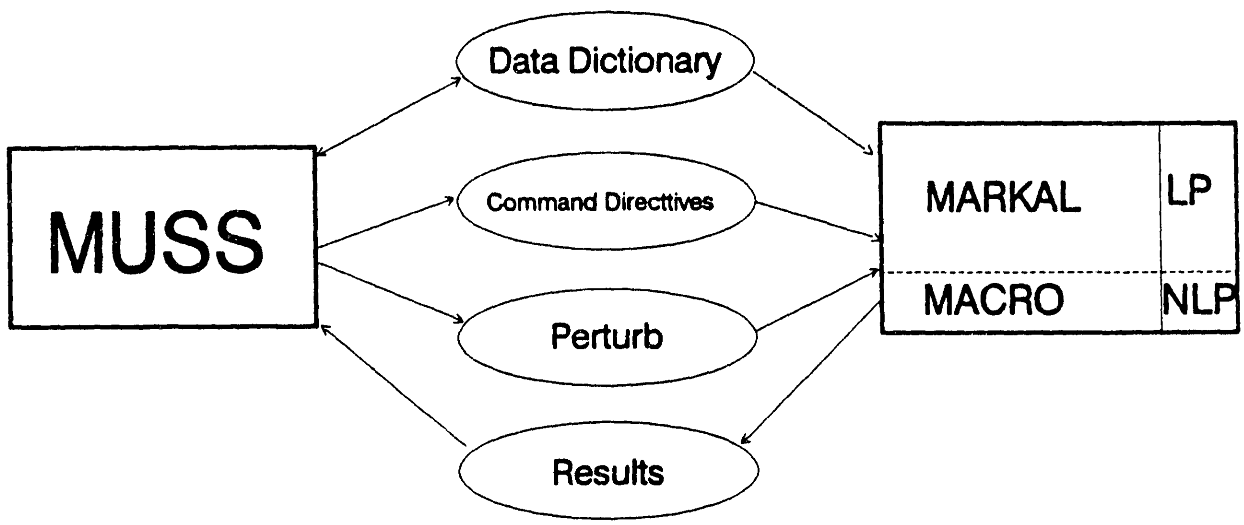
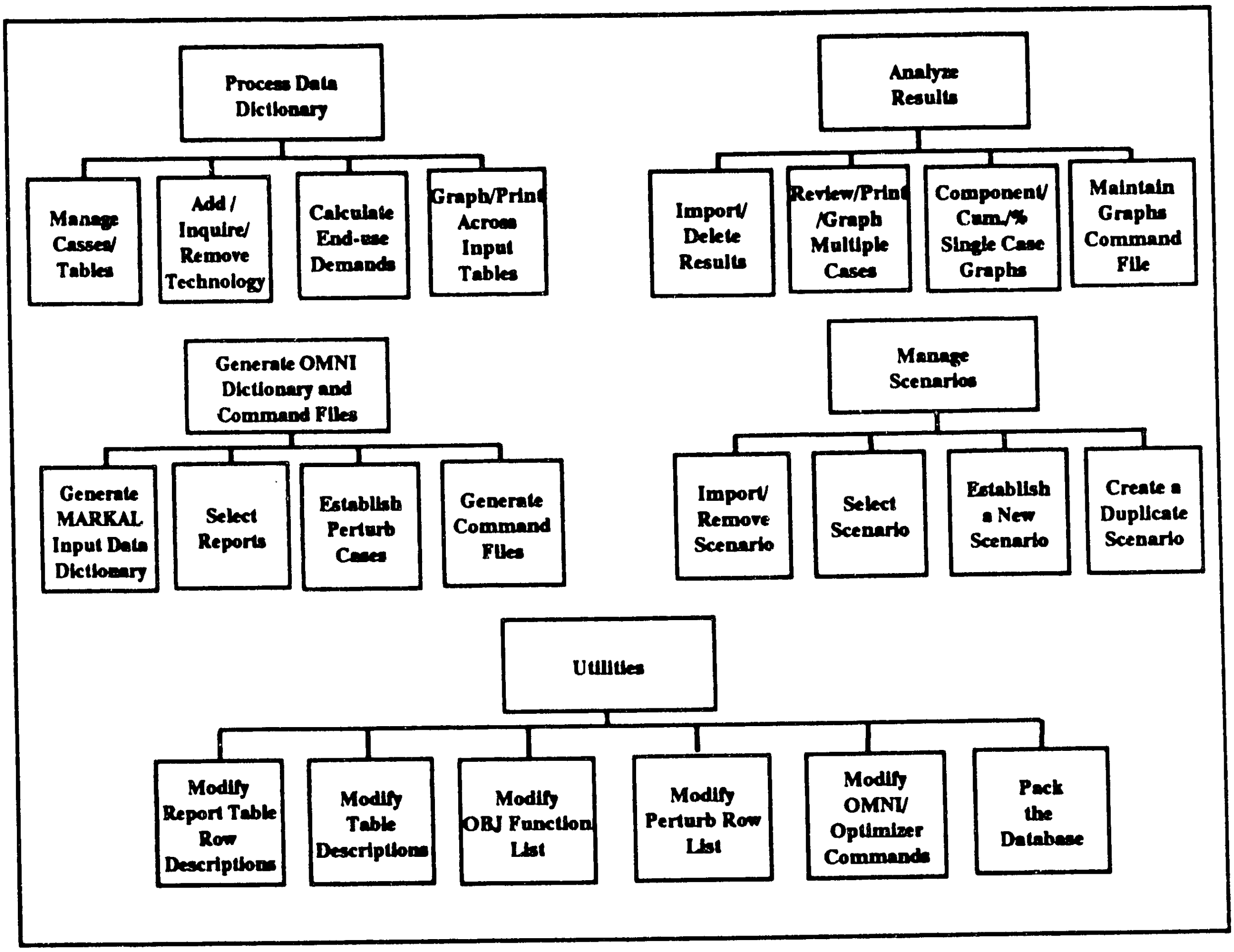


Figure 3

CAPABILITIES OF MUSS



MUSS System Overview

The above diagram shows the activities supported by each of the five main processing paths of the system.

Figure 4

BASE CASE: PRIMARY ENERGY USE

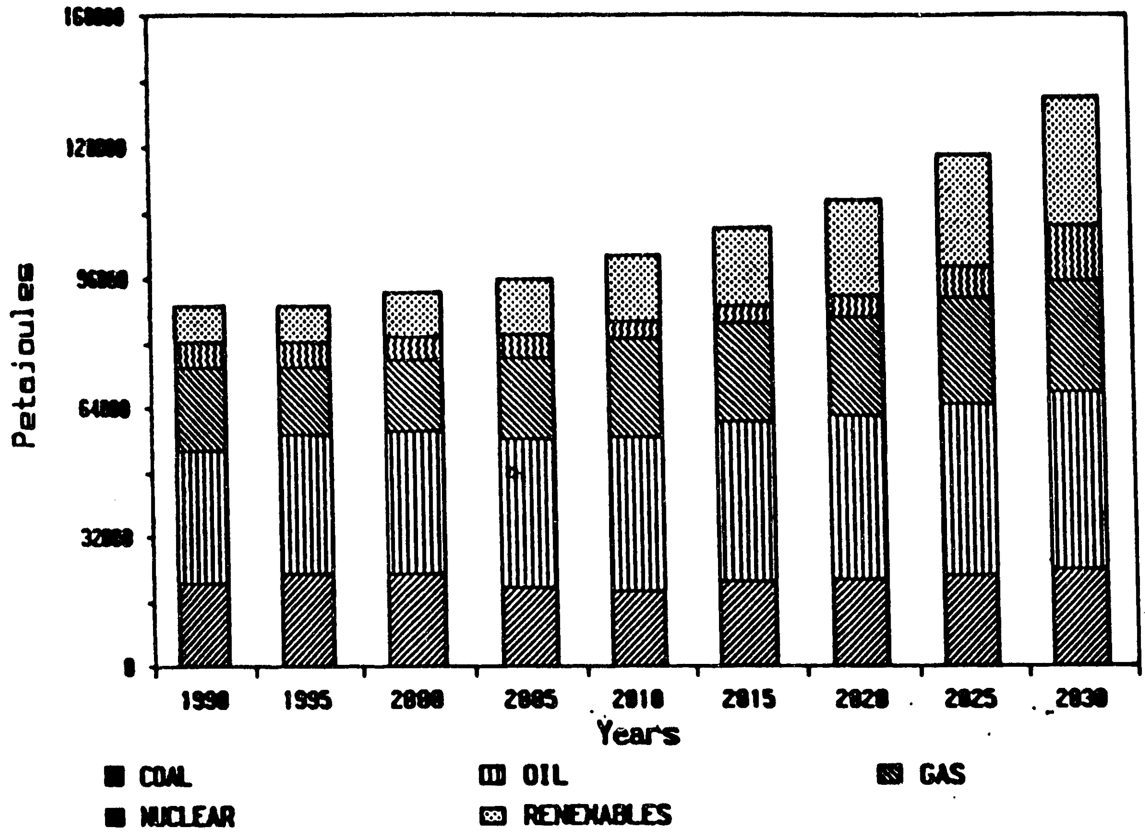


Figure 5

PRIMARY ENERGY USE IN EACH SCENARIO

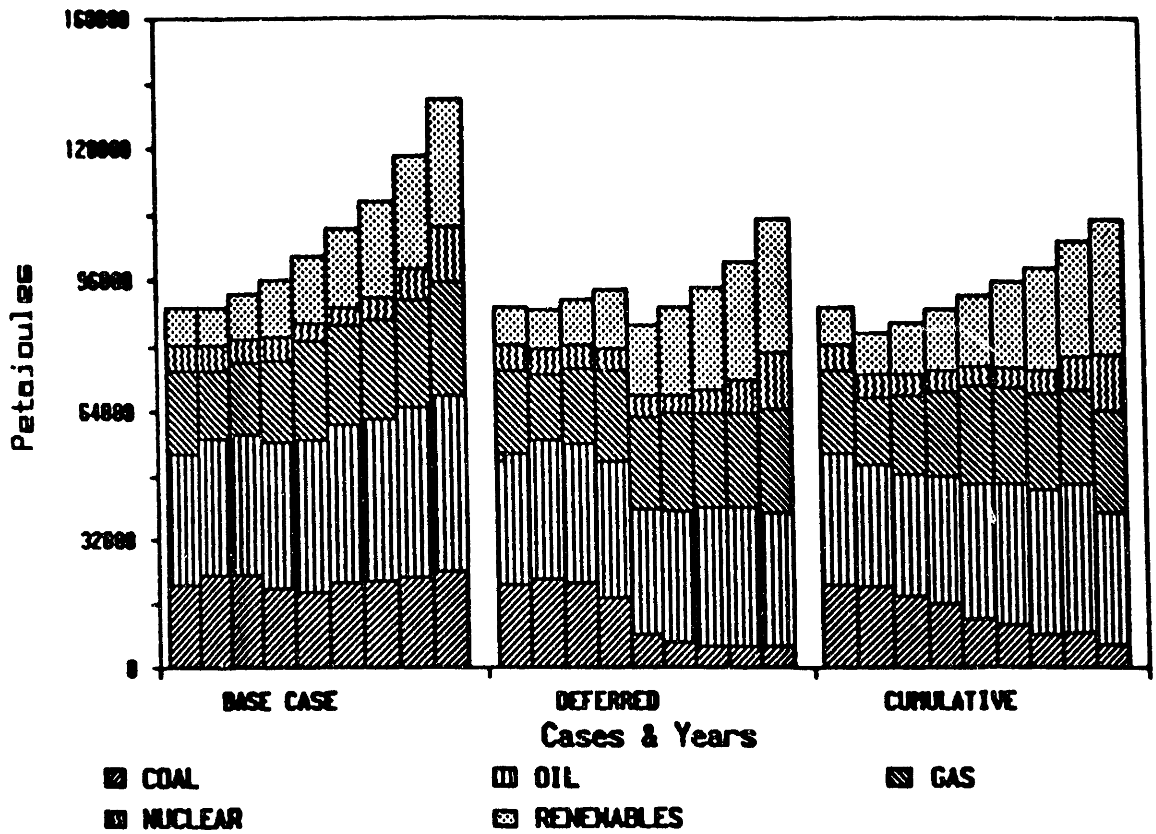


Figure 6
TOTAL USEFUL ENERGY DEMAND

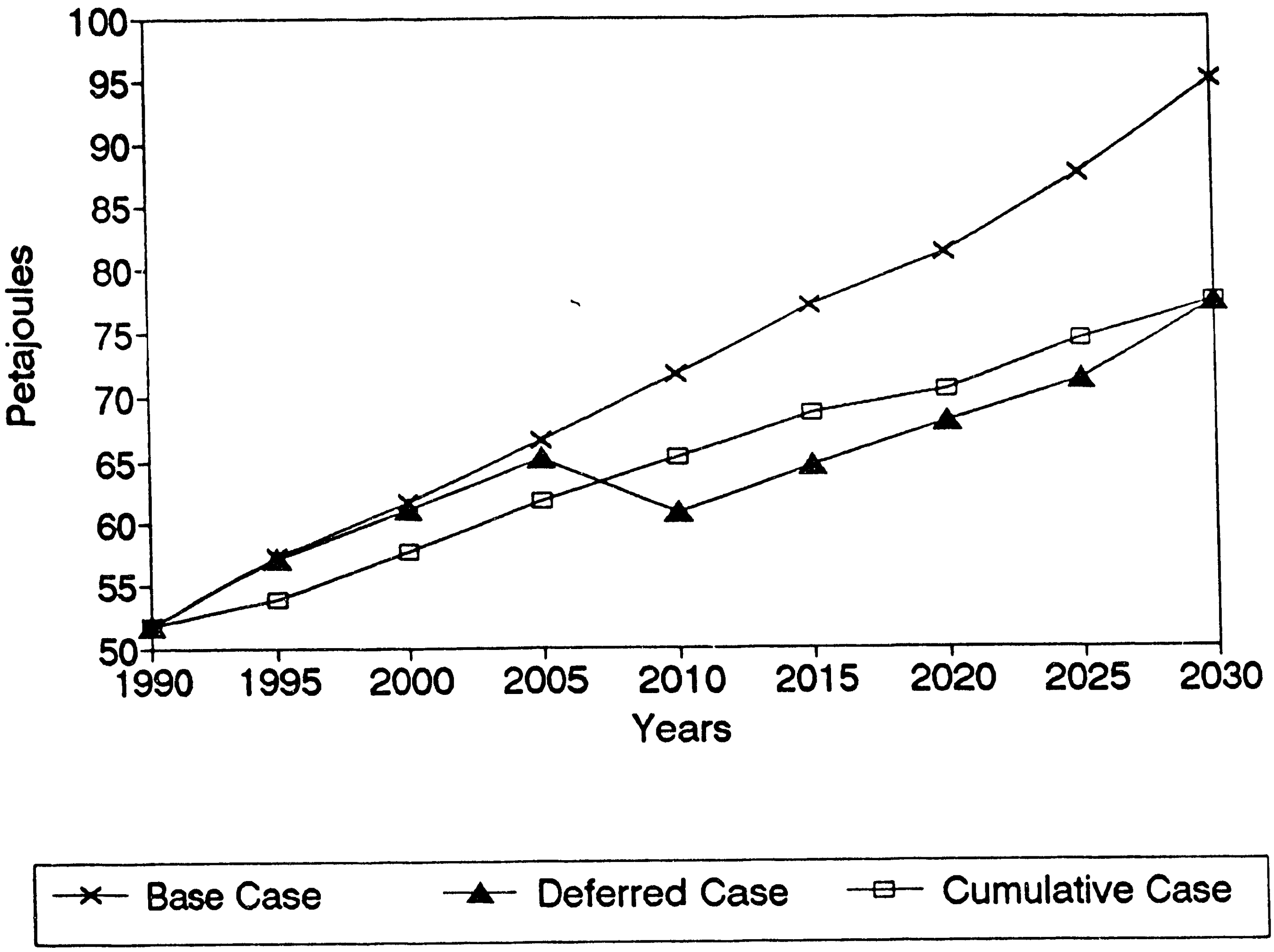


Figure 7

ENERGY INTENSITY: PRIMARY ENERGY/GDP

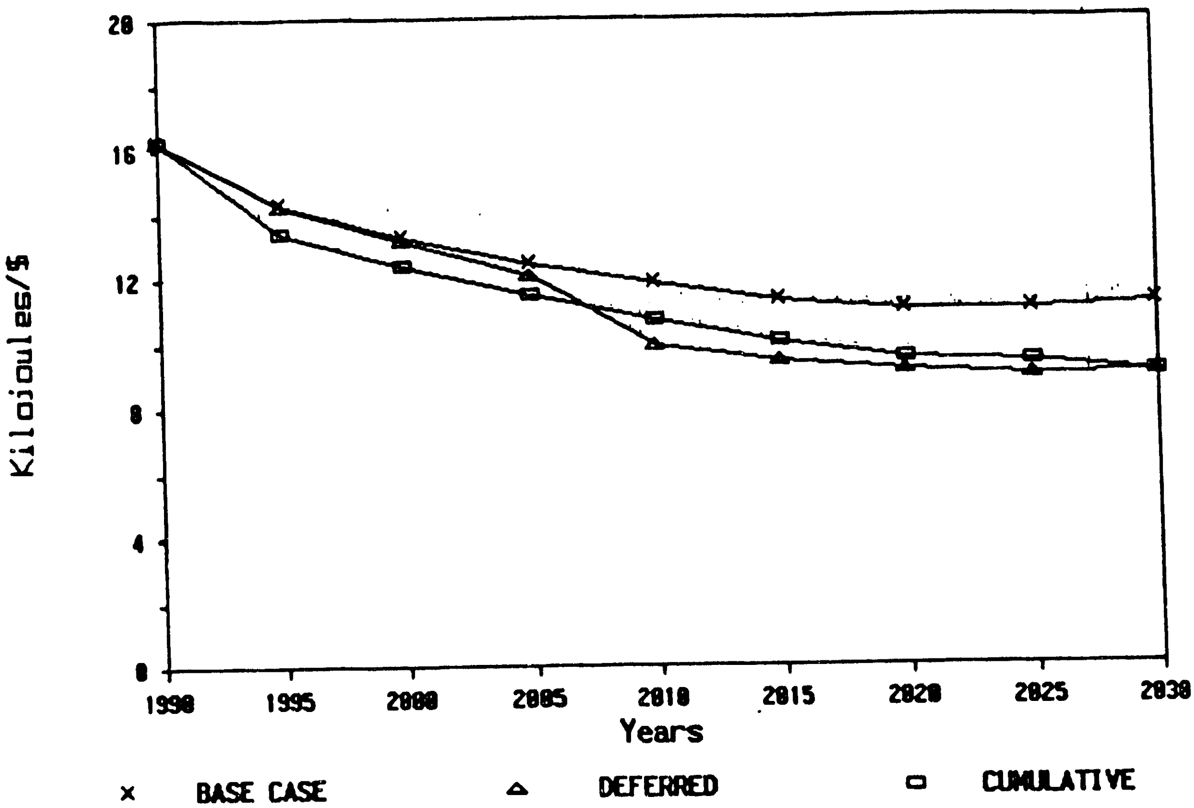


Figure 8
ENERGY INTENSITY: TOTAL UED / $ GDP

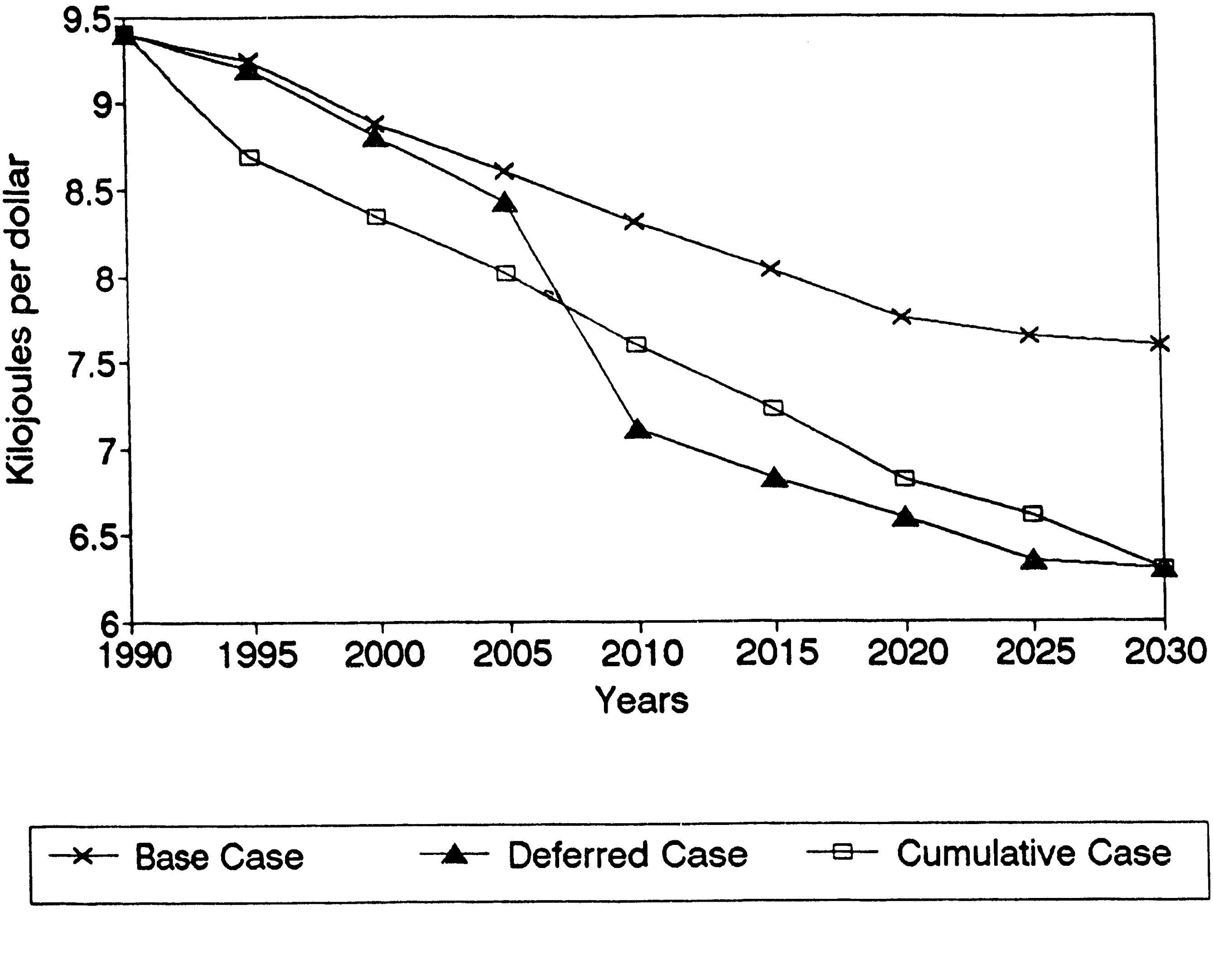


Figure 9

ELECTRICITY OUTPUT

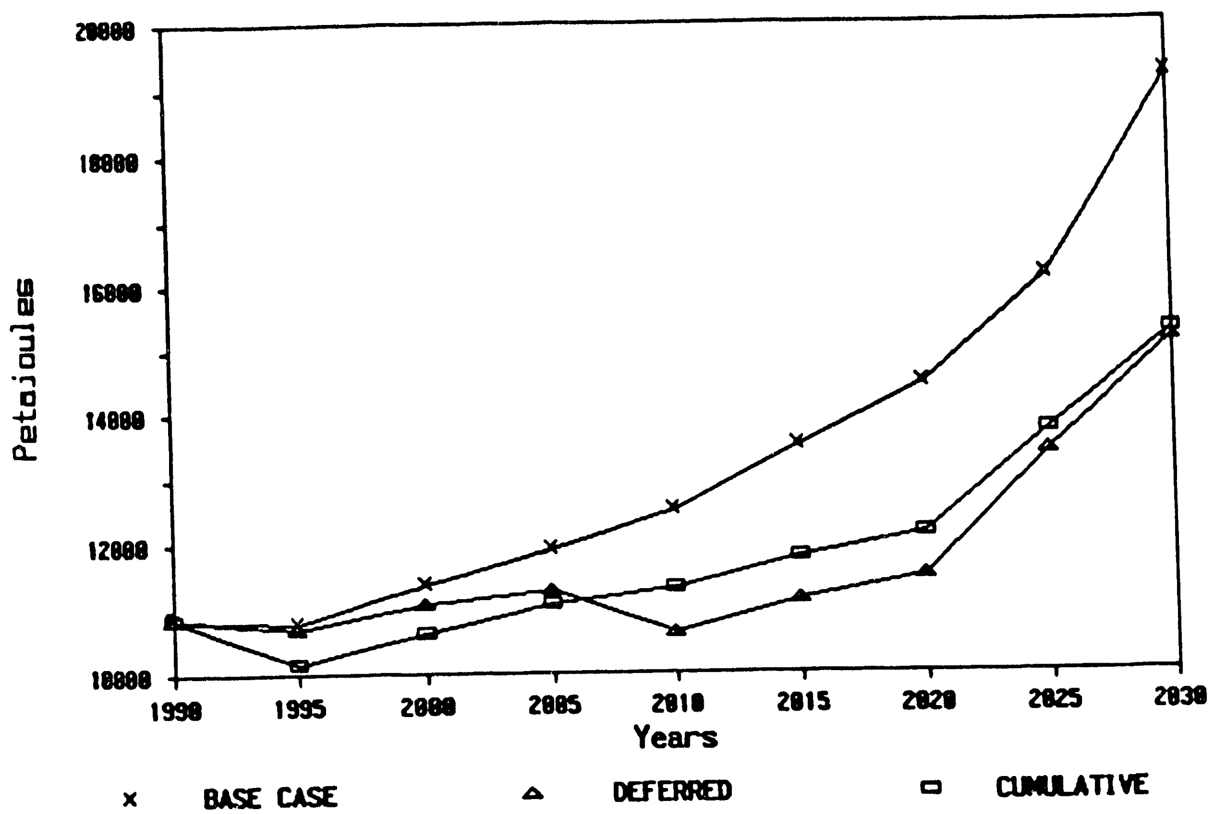


Figure 10

ELECTRICITY OUTPUT BY FUEL USED FOR GENERATION

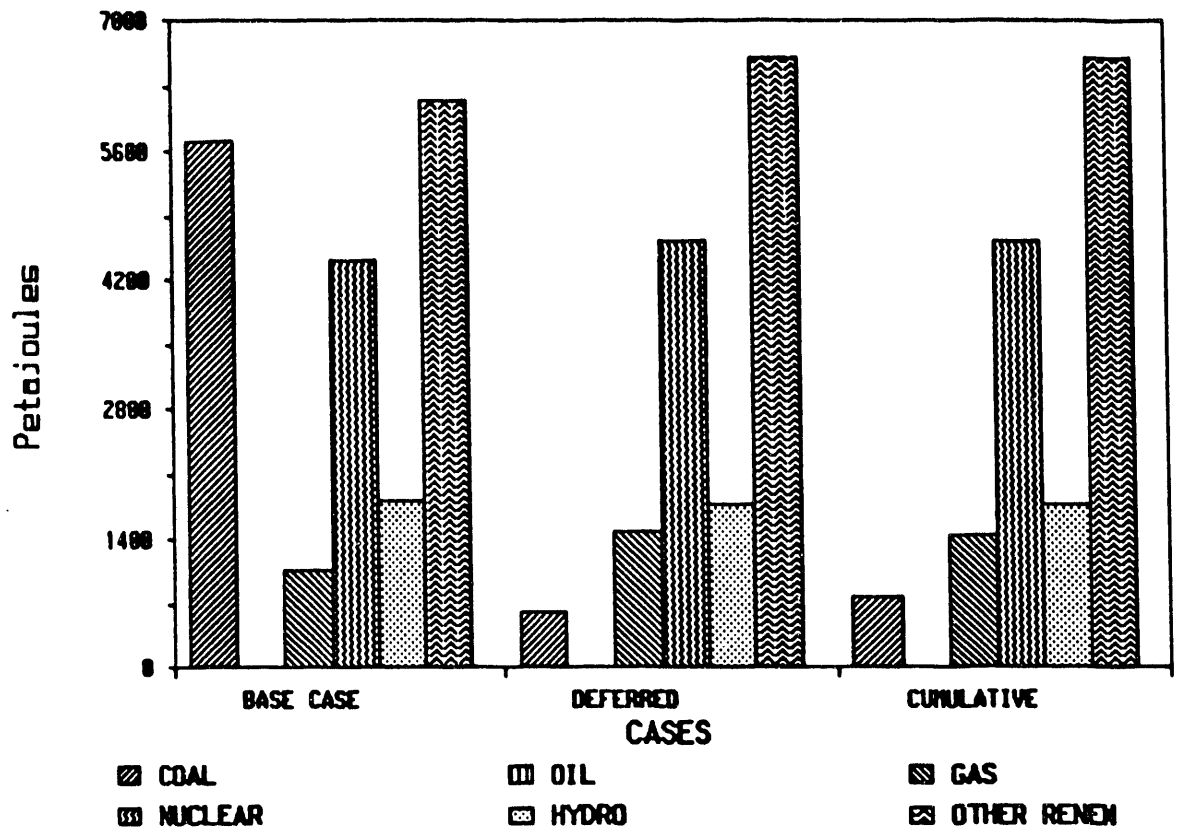


Figure 11

TOTAL CO_2 EMISSIONS

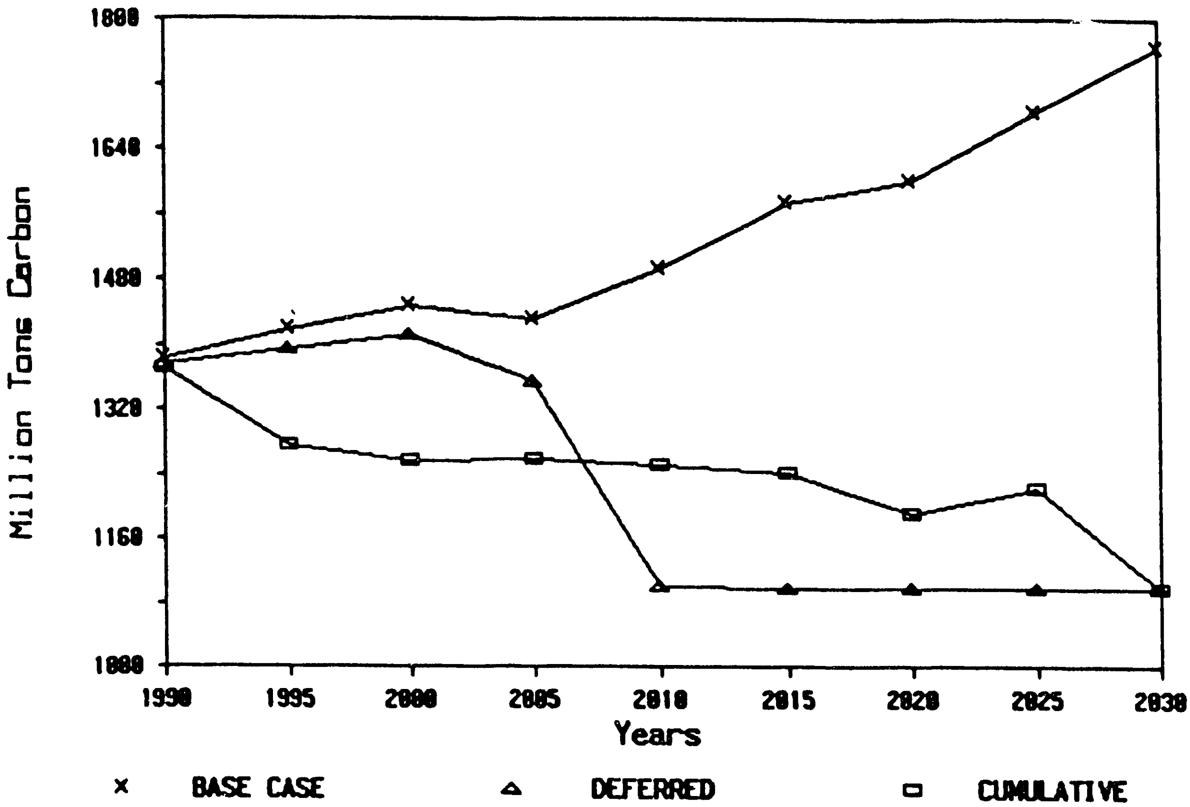


Figure 12

ENERGY COST

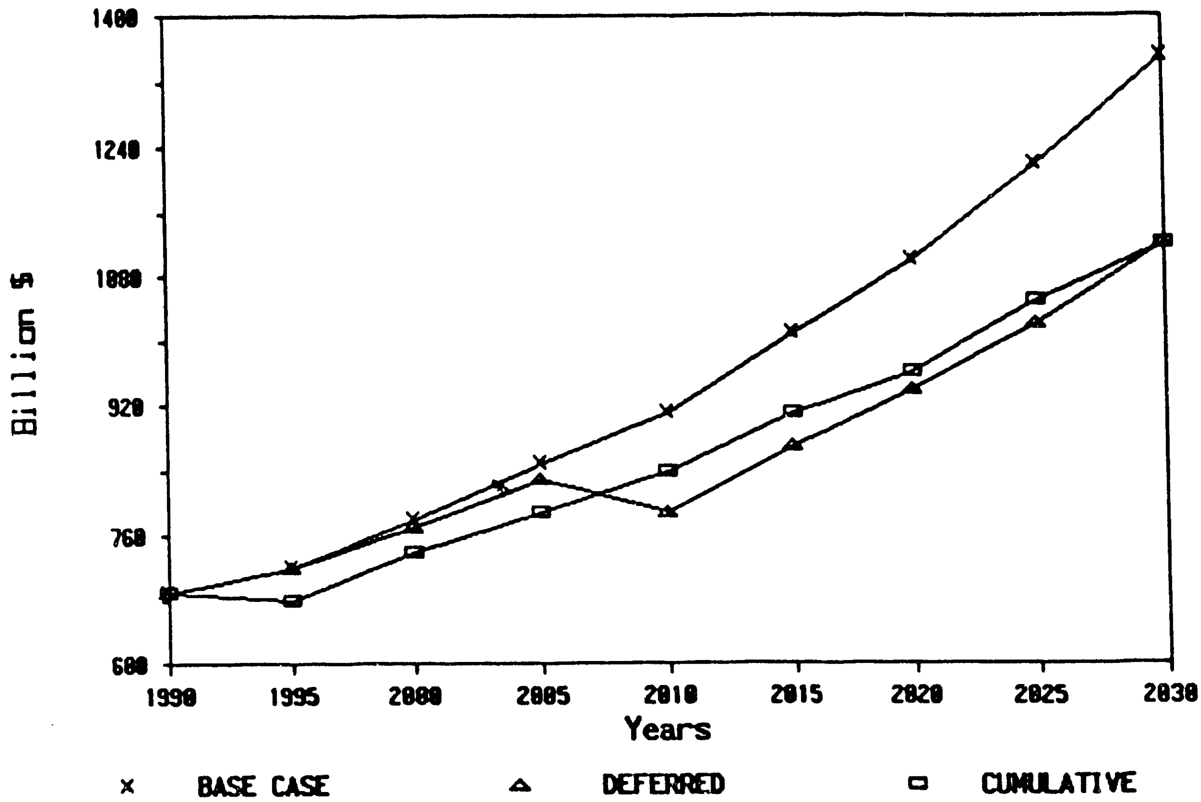


Figure 13

REDUCTION IN GDP FROM BASE CASE

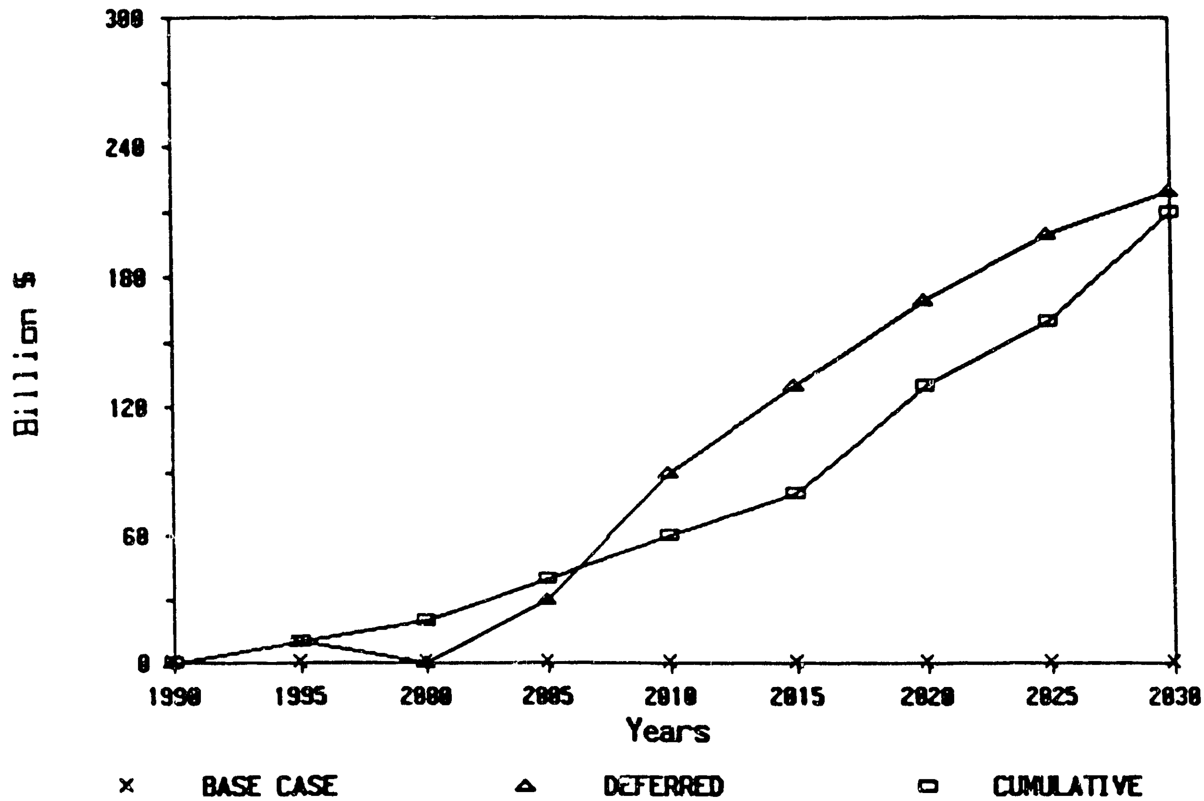


Figure 14

REDUCTION IN INVESTMENT FROM BASE CASE

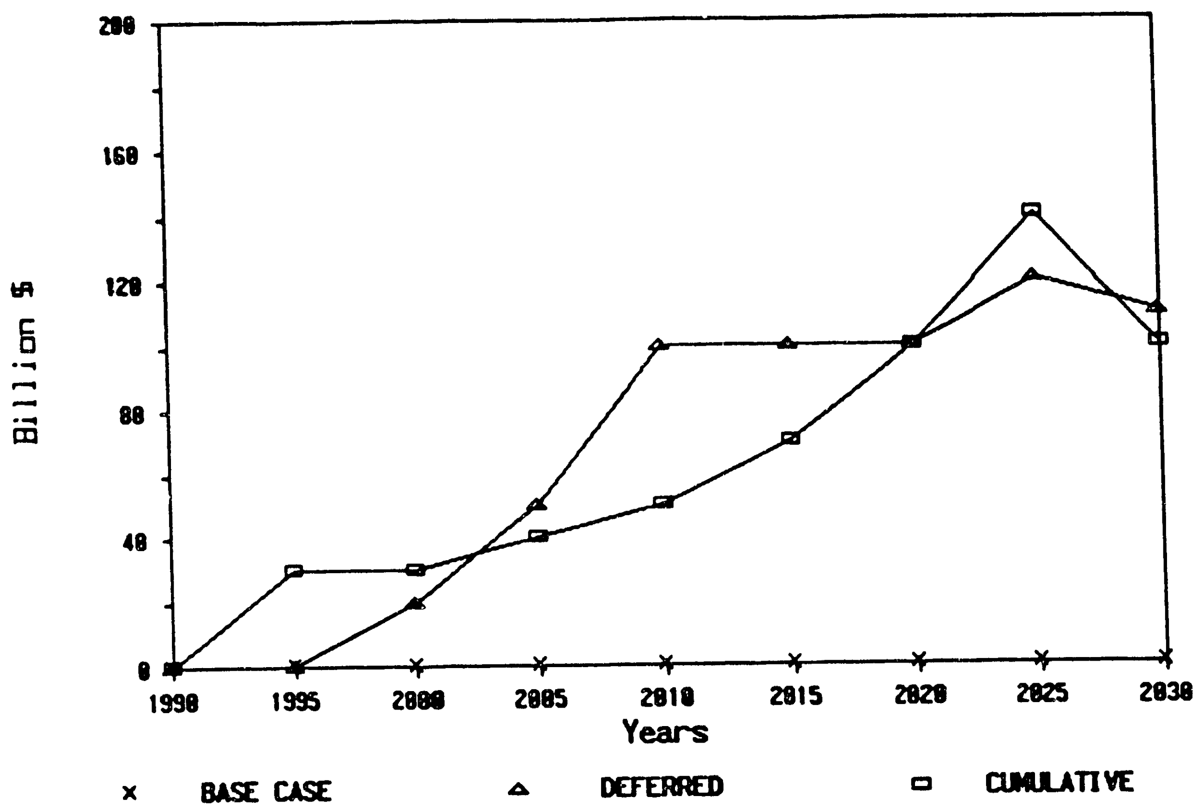


Figure 15

REDUCTION IN CONSUMPTION FROM BASE CASE

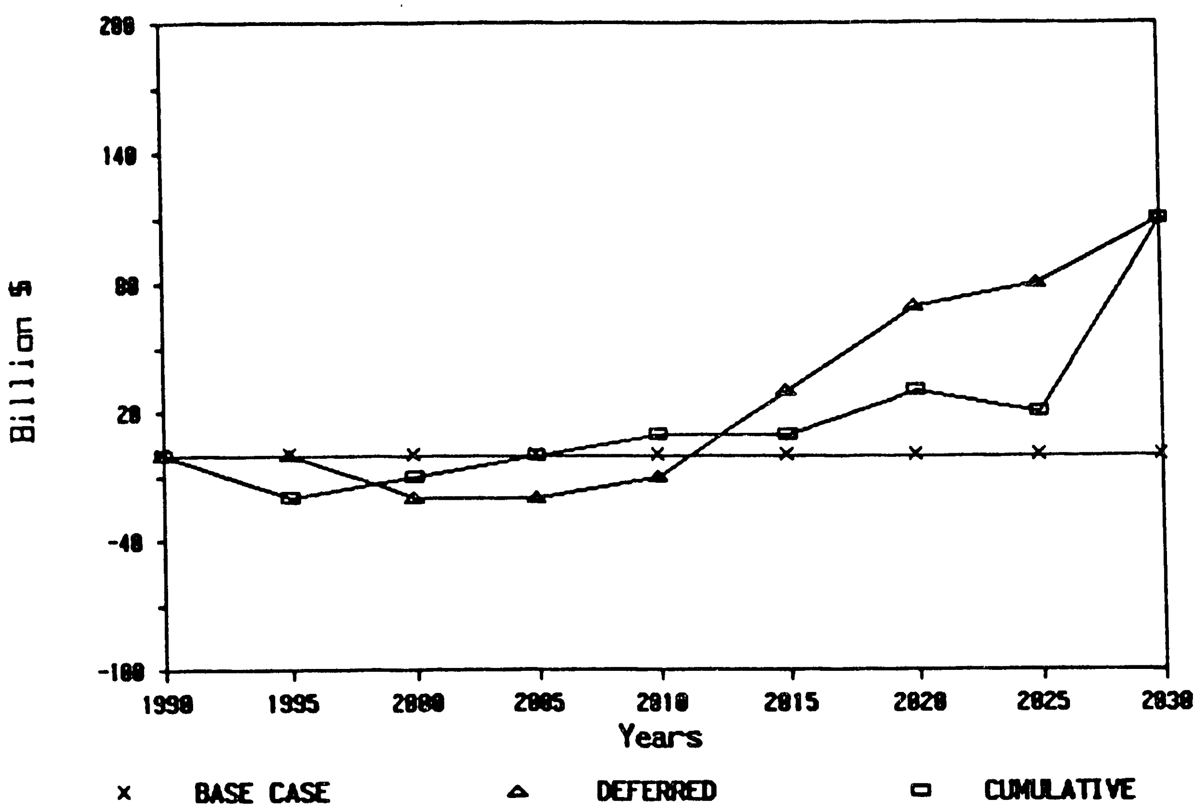


Figure 16

REDUCTION IN ENERGY COST FROM BASE CASE

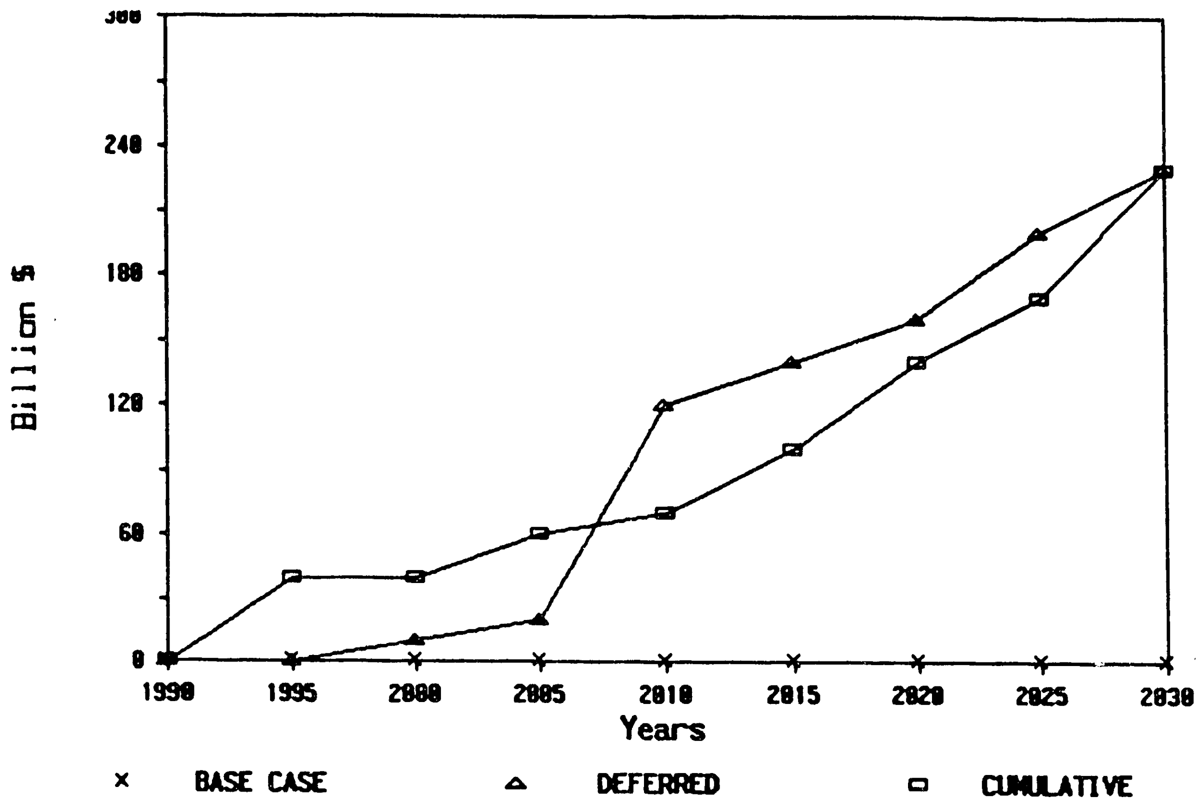


Figure 17

PRICE OF RESIDENTIAL WATER HEAT

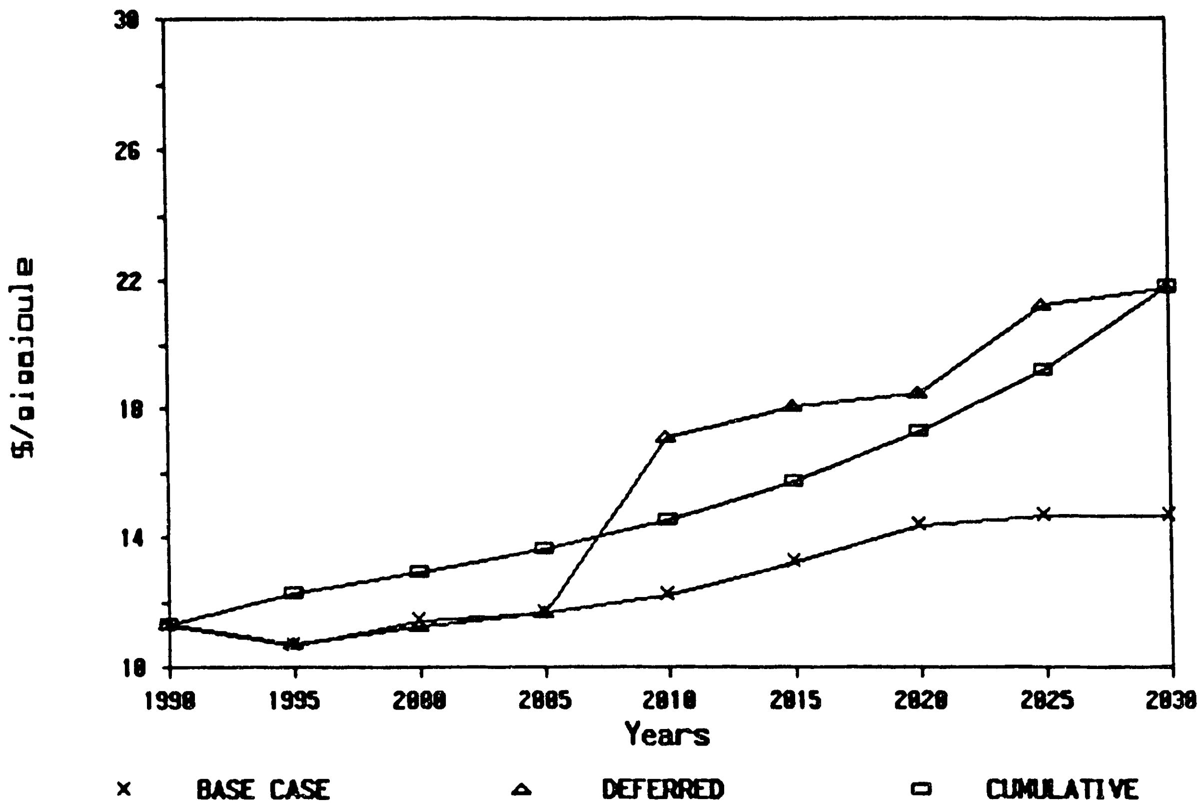


Figure 18

PRICE OF COMMERCIAL SPACE HEAT

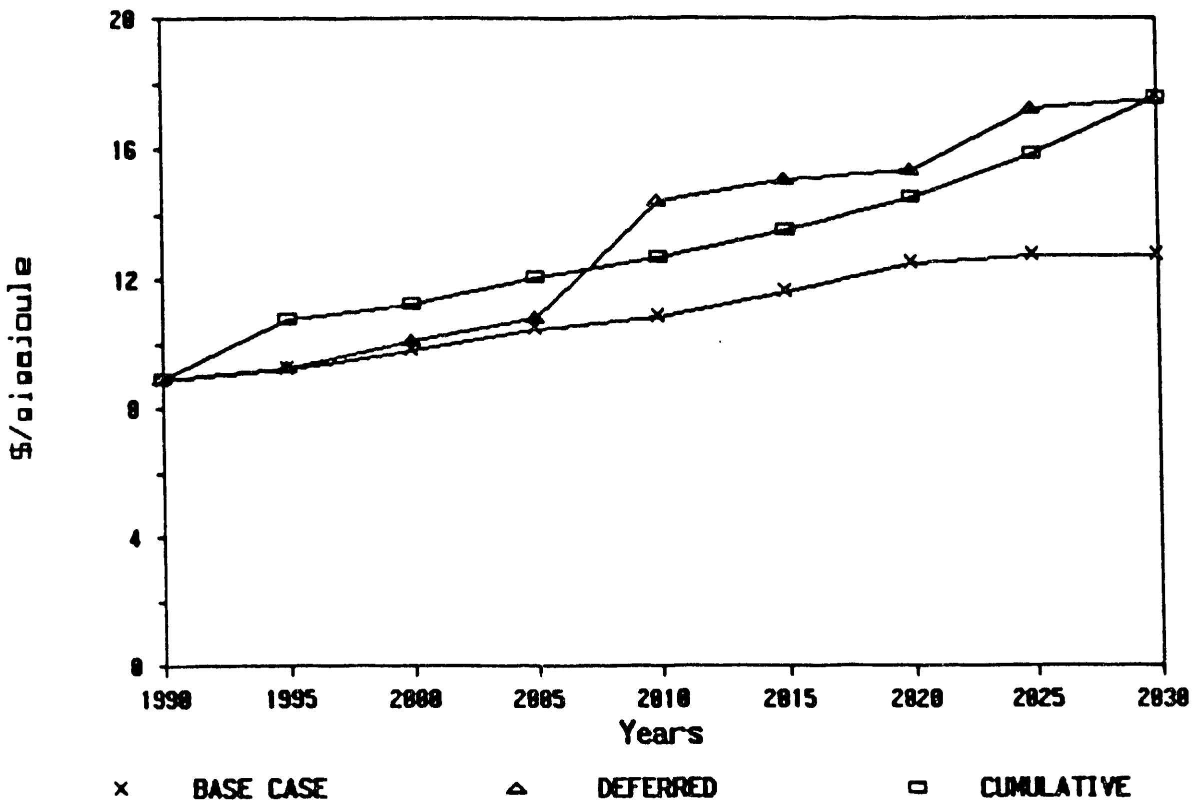


Figure 19

PRICE OF AUTOMOBILE TRANSPORT

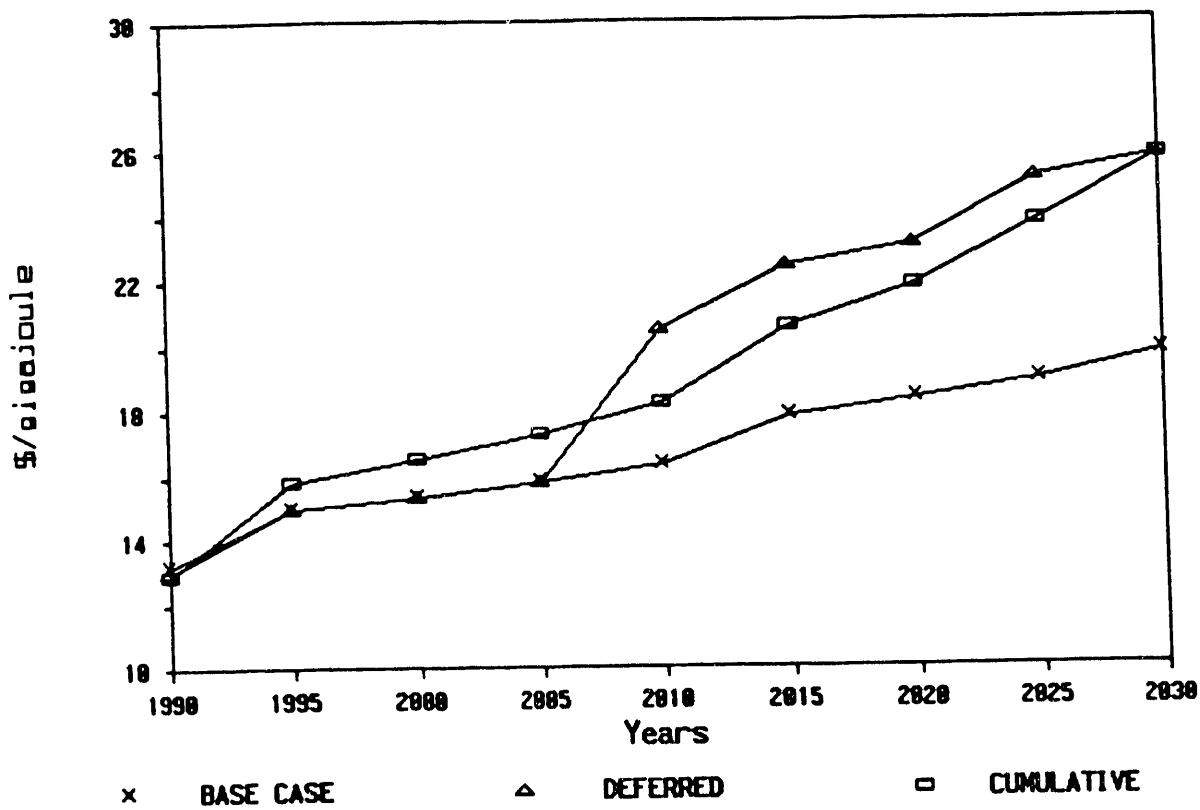


Figure 20

PRICE OF INDUSTRIAL PROCESS HEAT

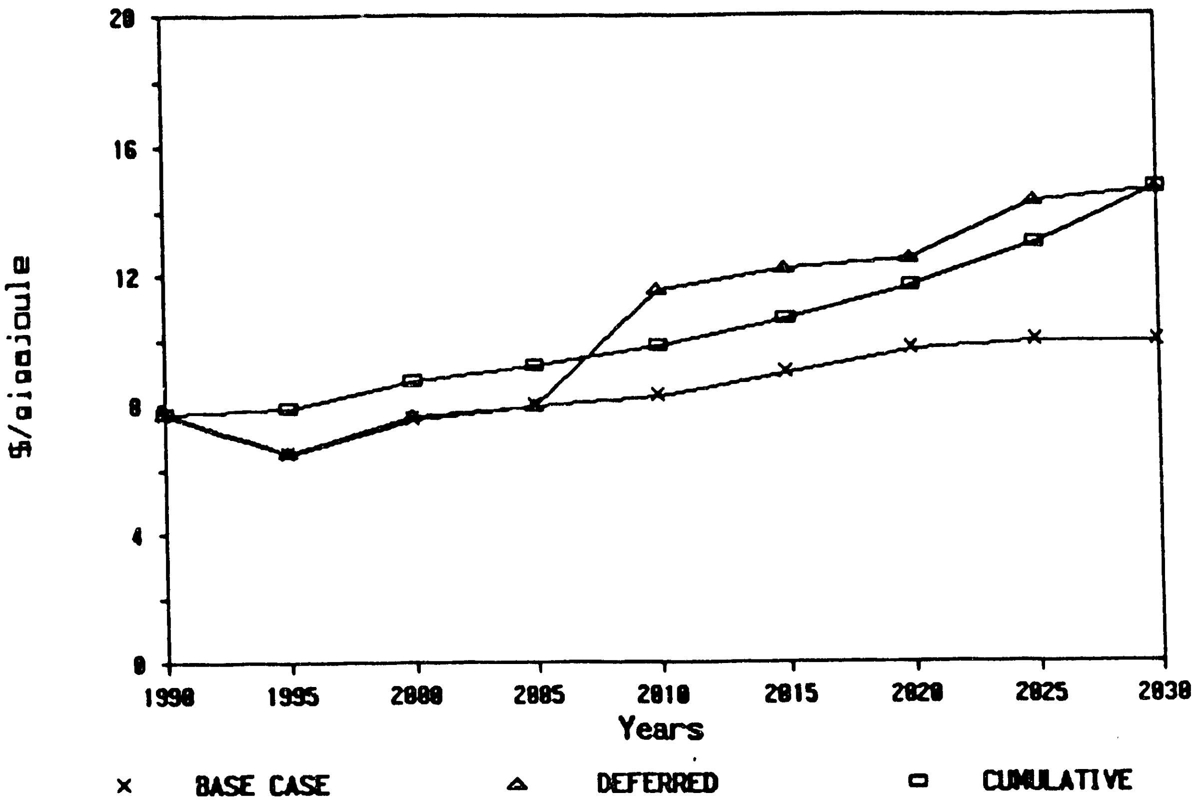
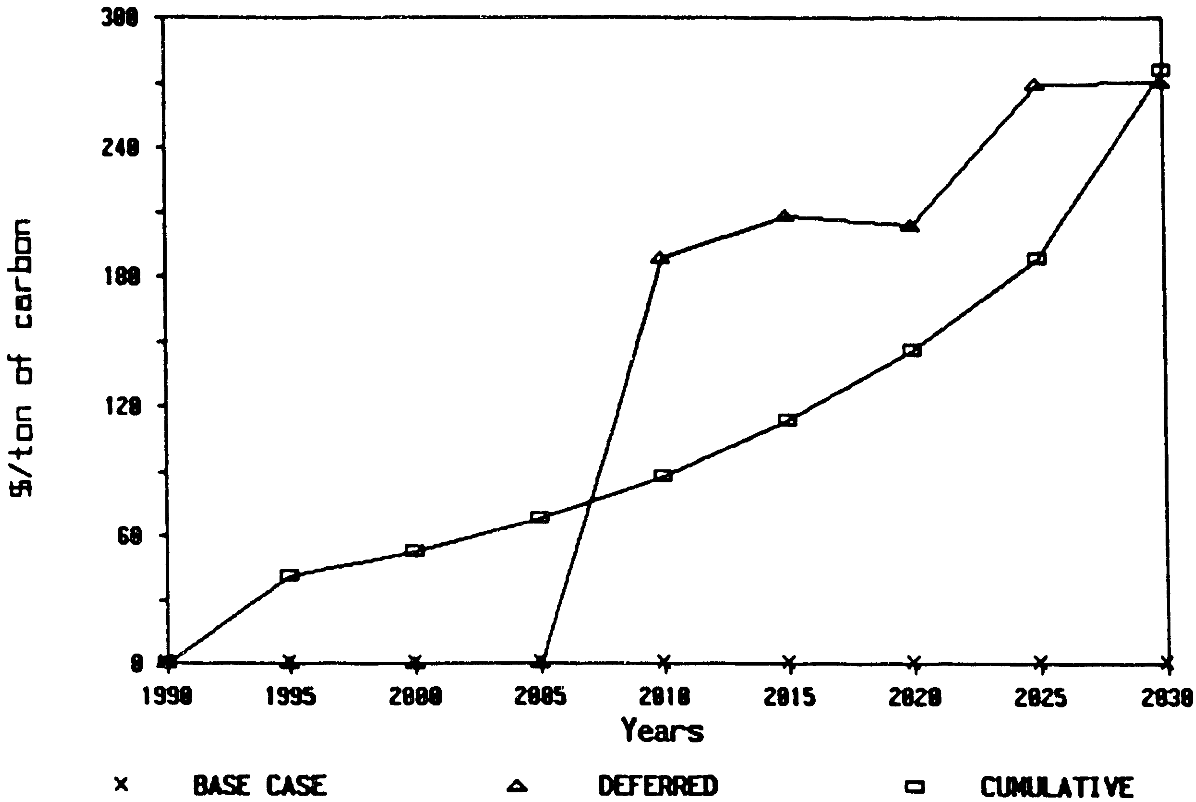


Figure 21

SHADOW PRICE OF CARBON EMISSIONS



Appendix A: Formulation of the MACRO Submodel and the Linkage Equations

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. Base year values are denoted by t = 1 (1990). The projection periods are identified as follows: t = 2 (1995), 3 (2000), . . . 9 (2030). 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 1990 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 avoid unrealistic short-term price-induced demand reductions. They also reduce the solution time and/or 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 MUSS data tables which the user is free to modify. For example, there are files containing 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. The linkage equations

The stand-alone version of MARKAL is documented elsewhere. For purposes of this report, it is sufficient to use the symbol X_j to denote MARKAL decision variable *j*. The cost and the useful energy demand rows are connected to the MACRO submodel through special-purpose linkage equations. All other MARKAL constraints are incorporated directly within MARKAL-MACRO.

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 supply coefficients $supply_{dm,t}$. These coefficients are positive if the MARKAL variable X_j is associated with supplying the useful demand category *dm* during time period *t*. We may then link the MARKAL supply activities to the MACRO demand variables through the following equations:

$$\sum_j supply_{dm,t} \; X_j \;\; = \;\; aeeifac_{dm,t} \;\; D_{dm,t}$$

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

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 for both "residual" and new capacities. 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. 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.

To avoid excessively rapid expansion of new technologies, MARKAL has been modified to include market penetration limits. These are not rigid upper bounds but are soft constraints on the variables $CAP_{tch,t}$ (the capacity for technology tch during time period t). Growth may be accelerated, but at a rising marginal cost determined by the level of the above-normal expansion variables $XCAP_{tch,t}$. These activities are valued not only because they enable an increase in current output but also because they provide a base for future expansion. Letting expf denote the *normal* five-year expansion factor, we then have:

$$CAP_{tch,t+1} \leq \text{expf}\ CAP_{tch,t} + XCAP_{tch,t+1}$$

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

$$\sum_j \text{cost}_{jt}\ X_j \quad + .5\ \text{qfac} \sum_{tch} \frac{(\text{ecst}_{tch})}{\text{expf capfy}_{tch}} (XCAP_{tch,t})^2 \qquad = EC_t$$

Note that the energy cost equations contain quadratic penalty terms associated with the above-normal expansion activities $XCAP_{tch,t}$. Suppose that the parameter qfac = 1, and that capfy_{tch} represents the maximum level of capacity that can be installed during the first year in which the technology becomes available. Each penalty coefficient is then chosen so that the marginal cost of providing capacity is doubled if the rate of capacity expansion is twice its normal level during the first period in which the technology becomes available. Over the long run, the marginal costs are determined by the capital charge coefficient associated with each type of capacity. During a period of rapid transition, however, the expansion constraints lead to a period of overshoot above the long-run level. These effects are moderated but not eliminated by the operation of the above-normal expansion activities.

A linear penalty form would require less computer time than the quadratic function employed here. With a *linear* penalty function, however, there would be a tendency toward bang-bang solutions in which all of the above-normal expansion occurs within a single time period. With quadratic penalties, it is typical for high-cost expansion to take place during more than one period.

To summarize: The cost coefficients are recalculated, and are employed to link the MARKAL variables to the macro energy costs. Similarly, the supply coefficients link the MARKAL variables to the macro useful energy demands. Quadratic penalty terms are introduced to smooth the rate of market penetration of new technologies. The remainder of the constraint rows are taken over directly from MARKAL.

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:

UTIL: $$\text{UTILITY} = \sum_{t=1}^{T-1} (udf_t)(\log C_t) + (udf_T)(\log C_T) / [1 - (1-udr_T)^5] \quad ,$$

where the utility discount rate for period t = udr_t = (kpvs/kgdp) - depr - $grow_t$, and the utility discount factor for period t = $udf_t = \prod_{\tau=0}^{t-1} (1 - udr_\tau)^5$. The exponents of 5 allow for the fact that the first T-1 periods are each 5 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

net rate of return on capital = (24%/2.4 years) − 5%/year = 5%/year

$grow_t$ = potential growth rate = 2%/year

∴ 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:

$$USE_t: \qquad Y_t = C_t + IV_t + EC_t \qquad t = 0, \ldots, T$$

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:

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

$$t = 1, \ldots, T$$

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 *kpvs*) 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 $L_{t+1} = (1+\text{grow})^5\, L_t$.

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 MCAP equations describe the dynamics of capital accumulation. Within each 5-year period, net new capital formation is determined by gross investment less depreciation. Let the annual depreciation rate be indicated by *depr*. Then the five-year capital survival fraction, $srv = (1 - depr)^5$. Since investment is measured as an annual flow, an accumulation factor of 2.5 is applied to the beginning and ending rate of investment so as to determine net new capital formation during the five-year period as a whole:

$$MCAP_{t+1}: \quad K_{t+1} = srv\ K_t + 2.5\ [\ tsrv\ I_t + I_{t+1}] \qquad t = 0, \ldots, T\text{-}1,$$

where $I_0 = (grow + depr)K_0$.

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.

$$TC: \qquad K_T\ (\ grow + depr\ )\ \leq\ I_T$$

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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