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Feature Article

Energy Policy Modeling: A Survey

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This survey provides an exposition of seven technoeconomic models that are representative of recent work on energy policy. The paper begins with several microeconomic concepts related to energy conservation and to energy-economy interactions. We then examine three representative medium-term models which deal with pricing, import policy and investment decisions in today's conventional supply technologies. Next, we analyze four studies dealing with longer-range issues—alternative research and development strategies for a transition away from depletable energy resources. The paper concludes with a summary of unresolved issues, and with suggestions on the future role of modeling in the public policy process.

DURING THE YEARS since the Arab oil embargo of 1973, there have been literally hundreds of analyses of U.S. and international energy prospects. Rather than attempt an encyclopedic coverage, this survey is intended only to introduce the reader to the field. We will concentrate on just seven *technoeconomic* models that are representative of recent work. In addition, there will be a selective bibliography, together with references to a number of other survey papers [10, 13, 37, 46, 62].

Inherently, energy policy is an interdisciplinary field. It involves economics, law, politics, engineering, resource geology, biomedical impacts, and environmental risk assessment—along with the methodologies that are already familiar to the operations researcher: optimization algorithms, simulations, decision analysis and econometric estimation. Unlike business applications in the private sector, it is exceedingly difficult to determine the impact of these studies. They are designed to influence

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congressional debates and to affect the climate of public opionion, not to guide decisions within individual corporations.

Before reviewing specific papers, it is essential to sketch out the nature of the energy policy debate. We will then describe several economic concepts related to energy conservation and to energy-economy interactions (Section 1). These ideas help us to understand why different models ascribe different roles to conservation and why there has been a continuing controversy over the long-term relationship between energy consumption and economic growth. We then examine three representative models which deal with pricing, import policy and investment decisions in today's conventional technologies (Section 2). Next (in Sections 3 and 4), we analyze four studies dealing with longer-range issues—alternative research and development strategies for a transition away from depletable resources such as oil, gas and uranium. Several of these studies employ sequential probabilistic analysis for R&D decisions under uncertainty. The paper will conclude with a summary of unresolved issues, and with a few suggestions on the future role of modeling in the public policy process.

The energy policy debate has both medium and long term aspects. For the medium term (say to 1990), the most urgent issues are those dealing with oil and natural gas which today provide 75% of U.S. energy supplies. Price controls and dependence on imports are among the principal themes of the medium term energy policy debate. For the longer term (the year 2000 and beyond) (barring unexpected new finds) oil and gas resources are likely to become increasingly scarce, and the policy debate concerns the nature of the transition to a post-petroleum world. For energy demands to continue growing at past rates, the most likely large-scale successors to petroleum would be coal and nuclear energy. Both of these sources are opposed by environmental defense groups. Instead, in one public hearing after another, the intervenors have urged reliance upon decentralized solar and other renewable energy sources together with conservation and simpler lifestyles.

Unlike most political debates, this one leaves little room for compromise. To the intervenors, the choice is of an either-or nature [45]. Economics and technology play only a limited role in the controversy. GNP growth is no longer automatically accepted as a good thing. The debate also concerns environmental values, nuclear safety, weapons proliferation, and political centralization within our society. It is unlikely that any one analysis—or one discipline—can deal with all these issues simultaneously. Models can yield only partial insights. Instead, it appears more reliable to depend upon informal information flows back and forth between individual analyses, each designed to handle specific issues at an appropriate level of detail with respect to time, space, physical and environmental impacts.

One can also hope that processes such as *counter modeling* and *third party assessment* will help to distinguish between objective analysis and one-sided advocacy. *Counter* or *adversary* modeling has been described as follows by Greenberger et al. [32, p. 334]: "Because of their flexibility, models can do more than provide a framework for debate. They can become the instrument of debate." Adversary modeling can help to focus attention on the issues that are critical to a particular problem and thereby avoid unnecessary and time consuming efforts on peripheral detail. This can happen, however, only when both sides accept a common analytical framework, and when they are in agreement on fundamental social objectives. Without such agreement, any modeling process will be an exercise in futility.

1. ENERGY-ECONOMY INTERACTIONS: THE ROLE OF CONSERVATION

It is generally agreed that the GNP growth rate is one of the primary determinants of energy demands. If GNP and other time trends are the only factors affecting demands, a model will be described as one in which demands are *exogenous* or *fixed,* and the objective is to minimize the costs of energy supply. This approach worked reasonably well during the 1950–1970 era when there were no abrupt discontinuities in energy prices.

For the post-1973 world, however, demand trend extrapolation has proved distinctly unsatisfactory. Increasingly, it has become apparent that energy models must allow for price-induced conservation. Sometimes this is done through *partial equilibrium* models in which GNP growth is viewed as an exogenous input variable. Partial equilibrium models imply one way linkage, whereas *general equilibrium* models allow for two way linkage between the energy sector and the rest of the economy. The rate of GNP growth is itself then affected by rising energy prices. Post-1973 economic history suggests that this distinction is not altogether an academic nicety.

Partial equilibrium analysis is typically based upon models such as that illustrated in Figure 1. This figure refers to a single energy form—quads (quadrillions of British thermal units) of *primary* energy (e.g., crude oil at the wellhead)—in a single time period. Consumers' willingness to pay is shown as a decreasing, continuously differentiable function of the amount of energy available to them, and producers' incremental costs are shown as an increasing step-function of the amount to be supplied. (There are far more individual users than suppliers of energy. It is therefore typical to estimate consumers' demands statistically through econometric techniques which imply continuously differentiable demand functions. Energy supplies, however, are often estimated through technological process analysis. With linear programming employed for this purpose, supply responses will then be multivalued *correspondences* rather than single-valued functions of market prices. To be a general purpose tool, an energy market equilibrium algorithm must be able to accommodate both these types of input data.)

Supplies and demands are balanced through an equilibrium price, one which equalizes the consumers' willingness to pay against the producers' incremental costs. It is as if the economy were attempting to maximize the size of the shaded area (net economic benefits) in Figure 1. This is what leads to the similarity between market mechanisms and optimization models, both for this simple example and also for the more complex cases to be described below. Typically, these will involve more than one form of energy and more than one time period. There may also be energy-economy interactions—shifts in the partial equilibrium supply and demand curves described in the figure.

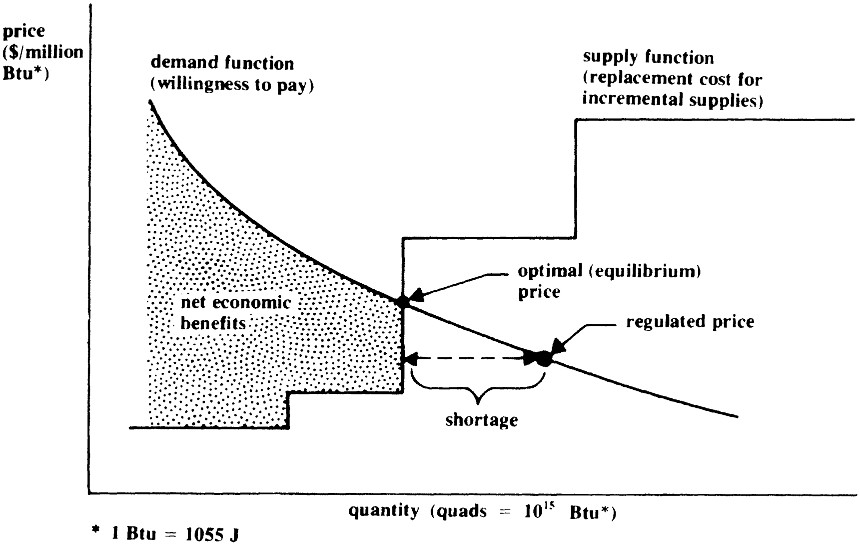

Figure 1. Market mechanisms and maximization.

Figure 1 illustrates both the concept of equilibrium prices, and also the consequences of price controls. A below-equilibrium price leads to shortages—gaps between the amounts that consumers will demand and producers will supply. Since 1973, neither the public nor many of their elected representatives have been prepared to allow domestic oil and gas producers to profit by raising prices to the international level that has been determined by the OPEC cartel. As a result, despite exhortations from three successive presidents, the United States has become increasingly dependent upon imported oil. This is the type of issue in which partial equilibrium economic analysis can be instructive, even in qualitative form. To quantify these effects, it is traditional for engineers and economists each to take a somewhat different approach.

Engineers tend to describe energy conservation in terms of specific measures such as (a) insulation to replace heating fuels in homes and other structures, (b) increased use of heat exchangers and of cogeneration within industry, and (c) the use of diesels to replace internal combustion engines in automobiles. Each of these measures would eventually become cost-effective if there were a sufficient rise in the price of energy. On the other hand, as a summary of individual phenomena, economists employ the concept of a price elasticity here denoted by the symbol η. This means that for each 1% increase in energy prices, there will be a reduction of η% in energy demands—given sufficient time for the economy to adjust equipment, structures and lifestyles to this change. If we restrict our attention to GNP and energy price variables, a simple practical forecasting equation might then be:

$$\begin{pmatrix}\text{\% change}\\ \text{in energy}\\ \text{demand}\end{pmatrix} = \begin{pmatrix}\text{\% change}\\ \text{in}\\ \text{GNP}\end{pmatrix} - \begin{pmatrix}\text{price}\\ \text{elasticity}\\ = \eta\end{pmatrix}\begin{pmatrix}\text{\% change}\\ \text{in energy}\\ \text{price}\end{pmatrix} \quad (1)$$

Empirical econometric studies differ widely in their elasticity estimates. See e.g. [12, 20, 30, 38]. To fix ideas, suppose that the long term price elasticity of demand for primary energy is $\eta = 0.3$. Also suppose that the United States plans to maintain a long term GNP growth rate of 3.0%, but aims to reduce energy growth to 2.0% (in view of limited future supplies). To keep the arithmetic simple, let us neglect non-price conservation measures such as mandatory fuel economy standards for automobiles. Then equation (1) implies that energy prices would have to rise at $(3.0 - 2.0)/\eta = 3.3\%$ per year (in dollars of constant purchasing power) in order to limit demand growth to the supply-constrained level of 2.0%. At high energy prices, however, additional supplies would be forthcoming. Prices and quantities are interdependent. One cannot be projected in isolation from the other. This provides the motivation for partial equilibrium supply-demand models such as that already illustrated in Figure 1.

With a general equilibrium model, one allows for feedbacks from the energy sector to the balance of the economy. In this case, GNP growth and energy prices are themselves interdependent, and are not viewed as independent variables on the right hand side of equation (1). Large price increases may reduce the GNP sufficiently so as to exert additional downward pressure on energy demands. See e.g. the Hudson-Jorgenson [40], PILOT [18], ETA-MACRO [34, pp. 1–45], and Hudson-Jorgenson/Brookhaven [36] models.

To see the basic issues that are involved, it has proved convenient to drop the partial equilibrium price elasticity concept, and instead to represent the economy in terms of just two basic inputs—energy and all other items. (This model was originally proposed in [34, pp. 247–277], and the present exposition is based largely on that report. Although a highly aggregated analysis, it has been cited in congressional hearings, and has provided a unifying framework for two of the studies undertaken by the Energy Modeling Forum to compare different models under common assumptions [20, 65].) Note that energy is only a small component of the U.S. economy. As of 1970, the value of primary energy inputs did not exceed 4% of the GNP. At 1970 or even at current prices, this is something like an elephant-rabbit stew. If such a recipe contains just one rabbit (the energy sector) and one elephant (the rest of the economy),

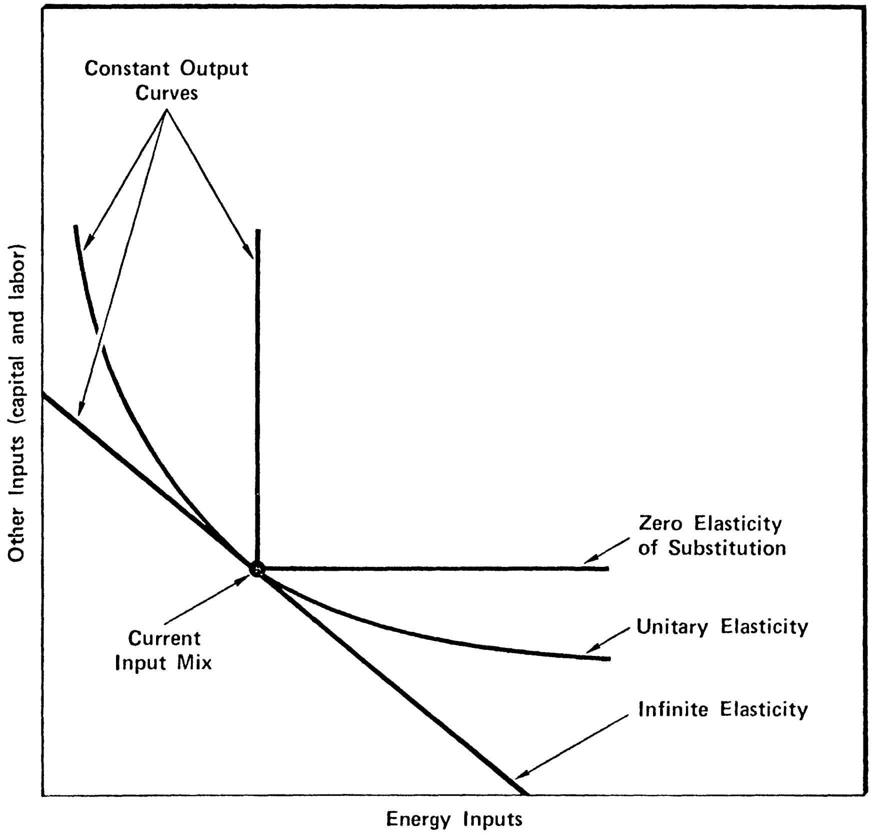

Figure 2. The elasticity of substitution concept (source: [20]).

won't it still taste very much like elephant stew? This analogy suggests that the energy sector need not necessarily induce major long term macroeconomic impacts.

For large price increases or for large reductions in the availability of energy we may employ the elasticity of substitution concept illustrated in Figure 2. The point identified as *current input mix* represents one possible combination of the inputs of energy and of other factors (capital and labor) used to produce a given level of output. These constant-output curves summarize the economywide potential for substitution between energy and other inputs. Three alternatives are shown with elasticities of substitution equal to zero, one and infinity. At any given point, holding output constant, and making optimal adjustments of the input-mix to relative price changes, this dimensionless, nonnegative parameter is defined as $\sigma = -(dq/dp)\ (p/q)$, where q and p denote, respectively, the quantity and price ratios of energy to other inputs. For more on this macroeconomic relation, see [3, pp. 52 ff.].

Today, most econometricians would agree that σ (the elasticity of substitution) when measured in terms of primary energy is a good deal lower than unity. The implications of several alternative estimates of this parameter are illustrated in Figure 3. As in equation (1), it is reasonable to assume that primary energy demand would grow at a rate close to that of the total economy if relative energy prices were to remain constant. At 3% per year growth from 1970, the GNP in 2010 would be approximately \$4.4 trillions, and total primary energy inputs would be 220 quads. This case is shown as the *reference point* in Figure 3.

Now suppose that for reasons of resource conservation, environmental protection, or national security, there is a need to reduce energy consumption. Suppose further that the economy's inputs of capital and labor remain constant. One way to achieve the reduction in energy consumption would be through an *energy conservation tax* with the tax revenues fully redistributed in an equitable pattern. Other policy measures (e.g., auto efficiency standards) could achieve much the same goal, but for illustrative purposes we shall simply describe all of these measures as an energy conservation tax. This tax represents the incremental value of energy at alternative consumption levels. Under these assumptions (and neglecting energy imports) the feedback issue can be posed through two questions: (a) What is the size of the conservation tax? (b) What is the resulting impact on GNP?

For alternative values of σ, the answers to these questions are illustrated in Figure 3. This graph depicts the GNP that would result at various levels of energy input, ranging from the reference value of 220 quads down to 70 quads if the inputs of capital and labor are held constant, and if energy costs also remain constant. The results are shown for elasticities ranging between 0.1 and 0.7. Each of these curves is highly nonlinear. Small reductions in energy consumption may be virtually costless, but large ones are expensive.

Thus, if $\sigma = 0.3$, it would require a 4.3% reduction in GNP to achieve a 50% reduction in energy consumption (110 instead of 220 quads). In percentage terms, this would be a small reduction. Nonetheless, it would constitute a large absolute economic loss—nearly \$200 billions' worth of the GNP in that 1 year alone.

For political purposes, the more relevant result may be the magnitude of the energy conservation tax. With $\sigma = 0.3$, it would require a tax of

$5.76/10^6$ Btu in order to achieve this level of conservation. (The OPEC-determined price of crude oil was $2.00/10^6$ Btu in 1975.) This means that the future tax might have to be nearly 300% of today's international energy price! At higher elasticities, the tax would of course be lower, and

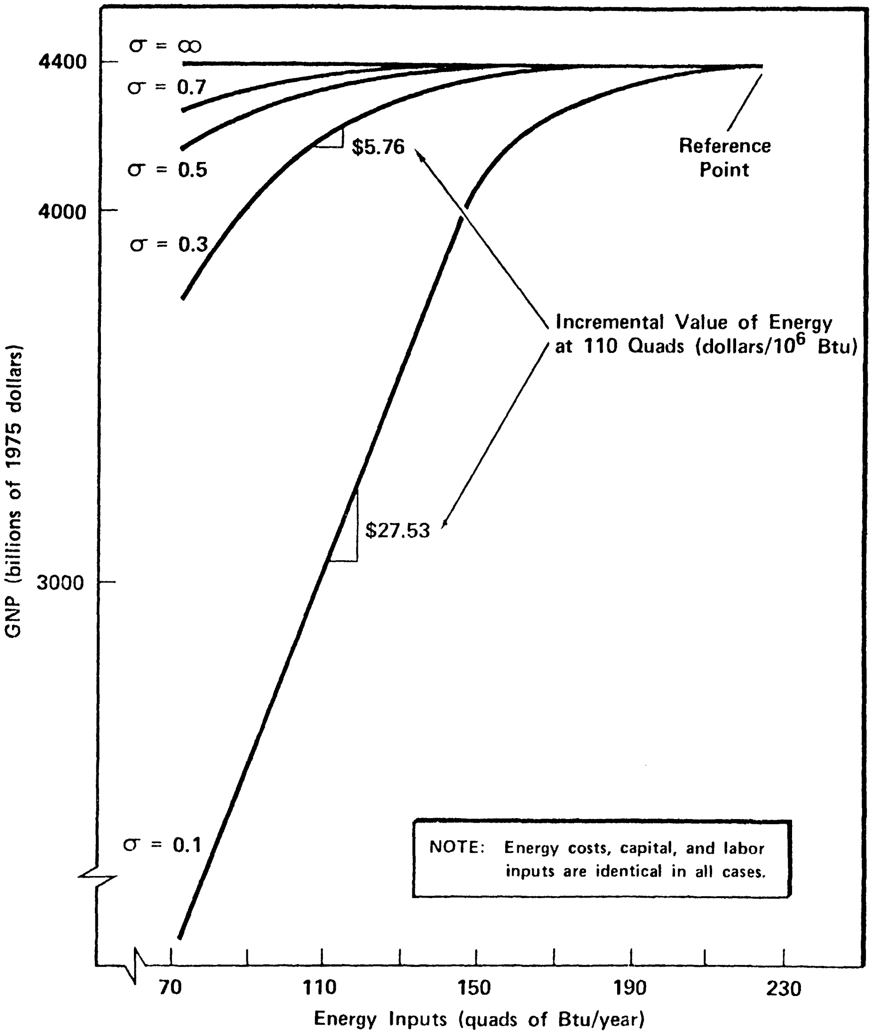

Figure 3. Economic impacts of energy reductions in the year 2010 for various elasticities of substitution (σ) (source: [20]).

the partial equilibrium assumption (one way linkage) would be more nearly appropriate.

2. MEDIUM TERM MODELS

Of the seven representative models listed in Table I, three are based on fixed demands, three are partial equilibrium, and one includes energy-

TABLE I

SEVEN REPRESENTATIVE STUDIES

	Medium-term (to 1990)			Long-term (2000 or beyond)			
	PIES	Kennedy	Baughman-Joskow	ALPS	BESOM	ETA, ETA-MACRO	Synfuels
Principal policy issues addressed	U.S. dependence on oil imports. Impact of domestic price controls	Pricing policies of OPEC oil cartel	Electric utilities pricing and equipment-ordering policies	Demonstration and commercialization of advanced nuclear reactors	Comprehensive accounting framework for R&D planning	Interrelations between U.S. economic growth, conservation, coal and nuclear energy	Demonstration and commercialization of synfuels technologies
Number of regions	U.S. divided into 9 demand regions; with transportation links	Non-communist world divided into 6 regions; with transportation links	U.S. divided into 9 demand regions; no transmission interties between regions	U.S. total	U.S. total	U.S. total	U.S. divided into 8 demand regions; with transportation links
Modeling methodology, time horizon and intervals	Interregional equilibrium through iterations between linear programming model of energy supplies and econometrically estimated model of energy demands in 1985 and 1990	International equilibrium through quadratic programming model of price-responsive oil demands and supplies in 1980	Year-by-year simulation to 1995, with capacity investment decisions based on energy price projections and load forecasts	Linear programming model of U.S. nuclear energy supplies and uranium resource depletion. Covers 120 years from 1969 through 2089, subdivided into 35 intervals of unequal length	Linear programming model for energy services delivered in 1985 and 2000. New supply technologies based on engineering process analysis	Intertemporal equilibrium through reduced gradient optimization algorithm. Price-responsive energy demands, resource depletion, and new supply technologies. Covers 75 years from 1975 through 2050, subdivided into 16 intervals of equal length. Sequential resolution of breeder uncertainties	Interregional and intertemporal equilibrium through recursive network algorithm. Covers 52 years from 1973 through 2025, subdivided into 17 intervals of unequal length. Decision tree refers to aggregated version of network model, with sequential resolution of uncertainties between 1985 and 1995
Pricing, energy demands and energy-economy interactions	Demands based on regulated or competitive prices, depending on policy scenario	Cartel-determined Persian Gulf crude oil price. Competitive supplies and demands for crude oil and products elsewhere	Electricity demands based on regulated prices	Fixed demands for nuclear energy	Fixed future demands for "energy services." Interfuel substitution based on engineering process analysis	Demand curves with own- and cross-price elasticities for electric and nonelectric energy. Energy-economy interactions included in ETA-MACRO (but not in ETA)	Fixed future demands for "end uses." Interfuel substitution based on market share price elasticity assumptions

economy interactions. (See bottom line of Table I.) Perhaps the best known federal government model is PIES (Project Independence Evaluation System), constructed in an unusually short period of time to provide an analytic basis for the energy independence goals announced in President Nixon's speech of November 7, 1973. In retrospect, this was an unfortunate choice of names, for it soon became evident that the United States would remain heavily dependent upon imports throughout the 1980s.

Space does not permit us to do justice to the algorithmic aspects of these individual models. Most employed either linear or nonlinear optimization to solve for market equilibria in much the same way as suggested by Figure 1. For example, Kennedy [44] postulated linearly independent market demand curves for refined oil products in each region. Then, following an idea originated by Samuelson [60], he showed that the individual market demand functions could be integrated into a *social welfare function* and solved by quadratic programming. At an optimal solution, the dual variables may be interpreted as market prices equal to long run incremental supply costs. The dual variables are also equal to consumers' incremental willingness-to-pay.

PIES. The Project Independence Evaluation System [25] was designed to estimate the impact of alternative federal policies—e.g., the decontrol of domestic oil and gas prices—on the import requirements of the United States during the 1980s. These policies were to be evaluated under major uncertainties with respect to the future international price of petroleum. The model projects the daily flow of energy from alternative supply regions to 9 demand regions in a typical future year—either 1985 or 1990. (See Figure 4.) PIES consists of an econometric demand model, a series of special-purpose supply models, and an integrating model.

The integrating model has a linear programming (LP) structure. It combines the outputs from each of the other components, and solves for market-clearing prices, supplies and demands (Figure 5). Step-function approximations to resource supply curves are taken from the special-purpose individual supply analyses, and are embedded within the LP structure of the integrating model. This cannot be done directly with the econometric demand models, for there the demand for a particular fuel depends both on its own price (through *own-price elasticities*), and also on the price of competing fuels (through *cross-price elasticities*).

Because of nonsymmetric cross-price elasticity terms, the PIES econometric demand functions do not integrate into a social welfare function. This means that conventional optimization techniques cannot be applied directly to solve for an equilibrium. Instead, an iterative procedure is employed. At each iteration, the cross-price elasticities are neglected, but the own-price effects are incorporated through step-function approximations within the LP structure of the integrating model. At each optimal

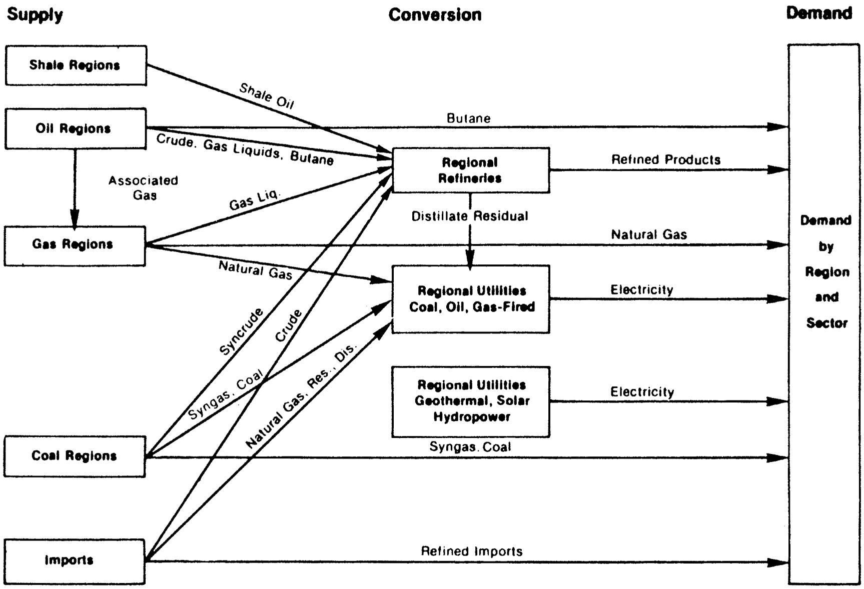

Figure 4. Flow of materials (source: [25]).

solution to the integrating model, there are dual variables (incremental costs) which serve as inputs to the econometric demand models for individual fuels. The econometric models produce a new set of own-price demand functions (again neglecting cross-price effects). These revised

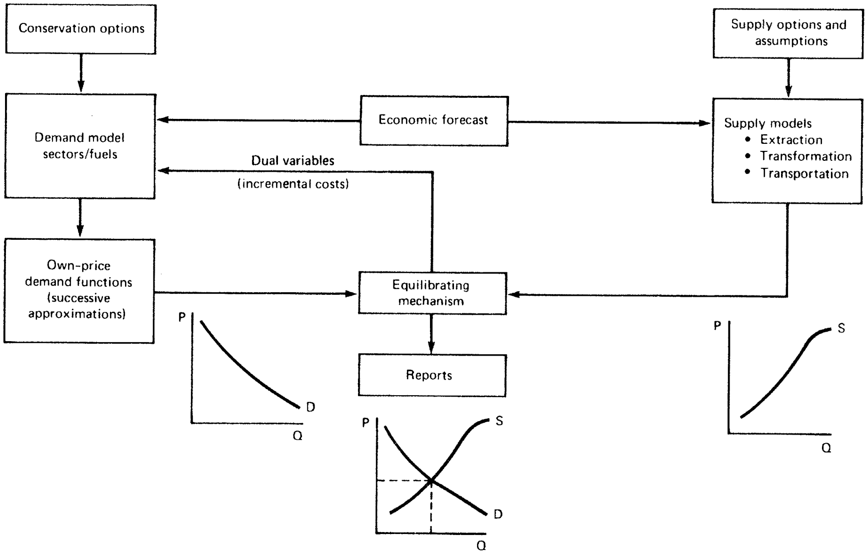

Figure 5. Integrating model framework (source: adapted from [25]).

demand curves are again incorporated within the integrating model, a new optimal solution is produced, and so on.

From an algorithmic viewpoint, PIES may be viewed as a variant upon the Dantzig-Wolfe decomposition principle [17]. Here too, prices are transmitted from the integrating model (the *master* in D-W terminology). Instead of *demand quantities* in the reverse direction, the econometric submodels here transmit price-responsive *demand functions*. (Unlike D-W, this demand information is discarded from one iteration of the integrating model to the next.) It is not difficult to construct counter examples in which the PIES numerical procedure will oscillate endlessly, and will fail to converge. In practice, however, the algorithm converged rapidly—presumably because the cross-price elasticity effects were of only second-order importance. See [2, esp. pp. 142 ff.]

Thus, despite its theoretical shortcomings, PIES turned out to be a useful practical tool. It was used extensively in the Project Independence Report [23] of the Federal Energy Administration (FEA). It was also used in the FEA's 1976 annual report, "The National Energy Outlook" [25].

Unlike standard optimization methods, PIES permitted policy analysts to evaluate legislative proposals for pricing formulas other than those based on dual variables (i.e., with marginal costs equal to incremental willingness-to-pay). PIES could therefore be used for *counter modeling* to clarify the differences between proponents and opponents of alternative measures for the decontrol of oil and gas prices. This occurred, for example, when PIES projections were presented to the House-Senate Conference on the omnibus energy bill for 1975 [24].

Regardless of the legislative outcome on oil and gas, it is clear that something similar to the PIES pricing approach will continue to be appropriate for modeling regulated public utilities such as electricity producers and pipeline companies. Regulatory commissions have consistently relied upon historical average cost formulas despite economic efficiency arguments in favor of marginal cost pricing.

Organizationally, the PIES decomposition structure made it practical to link submodels of different generic types. This permitted flexibility and decentralization within the existing bureaucratic structure of the FEA. Decomposition (division of labor) appears essential to the success of any large-scale modeling effort. See [5]. PIES was large, for it dealt with the entire U.S. energy system. We now turn to two smaller models. Each is focused on the supply, demand and pricing of a single fuel.

The Kennedy World Oil Model. Of the seven representative models surveyed here, this is the only one that is international in scope [44]. It deals with oil production, consumption, trade patterns and pricing. Alternative values are assigned to the international price of oil on the assumption that OPEC will act so as to maximize its net economic return.

This differs from PIES—which is focused on the United States alone—and in which the international price of oil is viewed as a key uncertainty, not as an OPEC decision variable.

Kennedy's is a multicommodity, multiregion single period economic equilibrium model, but its logic follows along the same lines as the single market equilibrium mechanism described at the beginning of this paper in Figure 1. It includes crude oil supply functions and also demand functions for four refined products in each of six regions of the non-communist world. Cross-price elasticities are taken to be zero. Linearity is assumed for each of the supply and demand functions. A market equilibrium may therefore be computed by solving a quadratic programming problem for maximum net economic benefits. Much like the linear programming models employed routinely for refinery coordination within individual oil companies, this one includes interregional transport and oil refining activities. The costs of these activities are subtracted from gross economic benefits (the areas under individual demand curves) to calculate the *net economic benefit* quadratic objective function.

Like others in 1974 [1, esp. p. 49], Kennedy concluded that the OPEC price was already too high for the cartel's own economic self-interest. By 1976, the climate of opinion had shifted. Using Kennedy's model, but with alternative input assumptions, Houthakker observed that OPEC might find it profitable to raise prices by 1980 or 1985 [39].

Regardless of whether oil prices are headed up or down, there are two major methodological limitations in Kennedy's model. First, it is static, and therefore excludes intertemporal phenomena such as resource depletion [see 53, 63] and the dynamics of supply and demand responses to higher prices. Second, it does not allow explicitly for competition between oil and alternative fuels.

Dynamic effects are included in analyses such as those of Cremer and Weitzman [15] and Pindyck [57]. Here again OPEC is viewed as a profit-maximizing monopolist and the rest of the world as a competitive fringe. Oil resource depletion is modeled by specifying that the incremental costs of extraction are an increasing function of the cumulative amount produced. Time lags in supply and demand responses are included in Pindyck's model. He concludes by projecting "a world price of \$13 to \$14 (per barrel) in the first year (1975), a decline over the next five years to around \$10, and then a slow increase" [57, p. 242]. This pattern is a characteristic result of incorporating adjustment lags in OPEC's net demand function. Adjustment lags may be exploited to gain short term profits.

Competing fuels and resource depletion are both included in the world energy model constructed by the Workshop on Alternative Energy Strategies (WAES) [66]. Country by country projections were made for 1985 and 2000 under uniform assumptions with respect to international oil prices and economic growth. To close the anticipated gaps between supplies and demands, WAES employed both "a highly constrained linear programming routine" [66, p. 255], and also informal expert judgments. In contrast to the sanguine views expressed in [1, 44], WAES concluded that: "Petroleum demand could exceed supply as early as 1983 if the OPEC countries maintain their present production ceilings because oil in the ground is more valuable to them than extra dollars they cannot use" [66, p. xi].

Baughman-Joskow. Like PIES and the Kennedy world oil model, the Baughman-Joskow Regionalized Electricity Model (REM) deals only with existing technologies. REM was constructed to analyze policy issues affecting electricity producers, consumers, regulators, and equipment vendors. Peak-load pricing, inclusion of work-in-progress in the rate base and the costs of environmental standards are among the issues it is

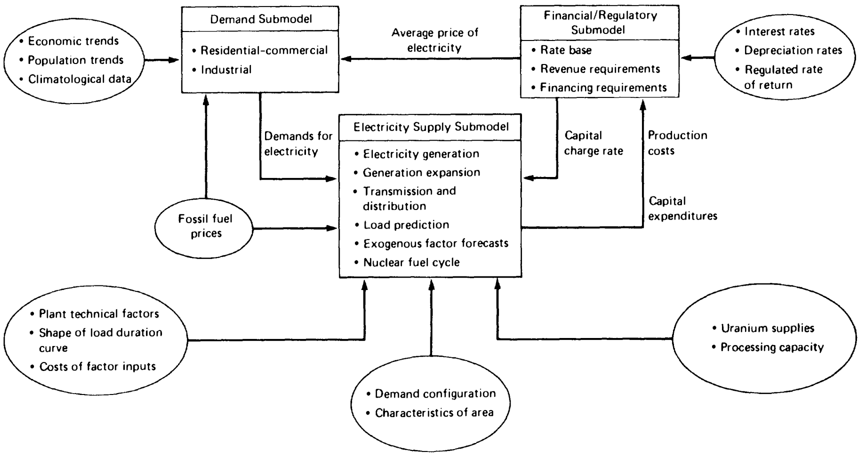

Figure 6. Schematic overview of the Baughman-Joskow model (source: [50]).

designed to address. Unlike previous electricity sector models [4, 12], it provides for simultaneous linkage of "supply, demand pricing, and financial behavior in a single integrated framework merging economic engineering behavioral models, financial models, and econometric models. . . ."

REM consists of three submodels—demand, supply, and financial/regulatory. Figure 6 shows how the three submodels are integrated, and identifies the information flows that allow them to be solved simultaneously. Like PIES, the econometric demand model forecasts regionalized electricity demands by the industrial and residential/ commercial sectors as functions of the prices of electricity and alternative fuels—coal, oil, and gas.

The supply submodel covers the engineering choices involved in operating and expanding an electric utility system. It is not an intertemporal optimization model. Instead, capacity expansion decisions are based upon single-period minimization of the levelized annual cost of meeting the electricity demands projected by exponentially weighted moving averages of previous periods. In general, these projections will differ from actual future electricity demands. Thus REM's electricity supply simulator is based on myopic behavior by electric utilities in contrast to multiperiod mathematical programming capacity expansion models, which imply perfect foresight. (If the load-duration curve is taken as a datum and if annual capital charges and fuel costs are independent of the capacity expansion program, it is possible to analyze each period's supply decisions independently. Dynamic models are needed, however, if the expansion program itself influences the prices of depletable resources such as uranium. This is why the ALPS long-term model (described below) is formulated in terms of multiple time periods.)

The financial/regulatory submodel simulates the process by which the electric utility industry raises investment capital, and sets the price of electricity in accordance with the administrative procedures of state and federal regulatory agencies. This submodel allows for the prices faced by consumers to differ from the marginal costs used for operating and capacity expansion decisions within the utility industry. Recall that this capability also exists in PIES, but there the linear programming calculations are based on 10-year perfect foresight.

In 1976, the Baughman-Joskow model was used to assess the future of the U.S. nuclear industry [41]. The study concluded that the industry and the Atomic Energy Commission were substantially overestimating nuclear power growth through the end of the 20th century. Serious questions were raised as to the future financial viability of the nuclear equipment manufacturers.

3. LONG TERM MODELS

ALPS (A Linear Programming System [33]). In 1966, at the request of the Congressional Joint Committee on Atomic Energy, the Atomic Energy Commission (AEC) conducted an overall review of the U.S. civilian nuclear program. As part of that review, an AEC task force developed an analytical framework to assess the benefits of alternate courses of electricity development. The resulting linear programming model, ALPS, is of interest for several reasons: (a) it was extensively used in 1969 [6], 1971 [7], and again in 1974 [8] to examine the benefits of new reactor technologies; (b) it represents one of the earliest applications of an energy technology assessment model by a government agency; and (c) it is one of the largest energy LP models in existence (4000 rows $\times$ 9000 columns).

Figure 7 summarizes the economic structure of the AEC benefit-cost framework. The model focuses on the supply side of the electricity market, and electricity demands are specified exogenously. The utility industry is treated as if it were a single company supplying electric power to consumers and receiving a flow of cash in return. As demands increase and old plants are retired, new capital investments are required. Other expenses include operating and maintenance (O&M) charges, taxes, fuel costs, and nuclear fuel cycle expenses.

The model is formulated so that electrical energy demands are satisfied at minimum discounted costs for capital investment, fuel, operating and maintenance over the planning horizon. For a given set of inputs, LP determines the optimal mix and the timing of transitions among alternative sources of nuclear power.

ALPS was designed primarily to study the trade-offs among different types of base-load nuclear power plants. For this reason, relatively little

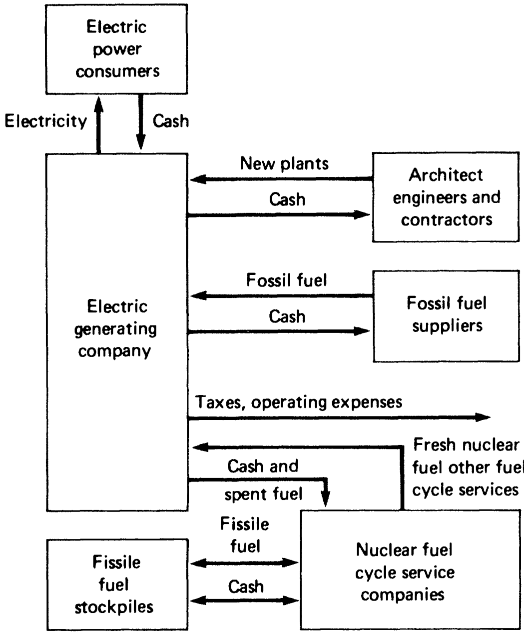

Figure 7. AEC benefit/cost analysis economic model (source: [8]).

attention was given to the analysis of fossil fuel units. In all but a few cases, the fossil-nuclear mix was specified exogenously, and the optimization was limited to the competition among alternative nuclear technologies: breeders and converter reactors. (ALPS was designed to be machine independent and more compact than the POWERCO, PACTOLUS, DAEDALUS, CLOTHO, LP, and MERCURY code series, used by the AEC in breeder benefit-cost studies prior to 1972. The version of ALPS described in [33] is virtually identical to that used in WASH-1535 [8].)

In view of its size, ALPS has relatively few degrees of freedom. The rates of capacity introduction and retirement are built directly into the model. AEC projections of nuclear capacity by plant type are followed until the year 2000. In the years after 2000, nuclear technologies are allowed to compete within the assumed market for nuclear energy. Phaseout constraints are specified to prevent established reactor designs from disappearing instantaneously as new and more economical plants become available. The time phasing is also intended to be consistent with the capacity of the industries for manufacturing heavy electrical equipment.

The size of ALPS is due largely to the number of time periods, and to modeling details for the nuclear fuel cycle. Uranium ore, mining, conversion, enrichment, fabrication, reprocessing, and storage costs are all included as basic input data. Annual demands through 2020 (for nuclear reactors, raw uranium ore, enrichment, and other fuel cycle requirements) are included in the reported output. To avoid horizon effects, the model extends to the latter part of the 21st century.

ALPS was used by the AEC in the preparation of its proposed final environmental impact statement on the liquid metal fast breeder reactor (LMFBR) (WASH-1535) [8]. This is the most detailed benefit-cost analysis of the breeder program to date. Breeder benefits are sensitive to a large number of uncertainties. These include uranium supply, capital costs, availability of the breeder and other advanced technologies, electrical energy demand, and the discount rate. In its attempt to identify an optimal R&D strategy, the AEC calculated breeder benefits for over 200 future scenarios. According to its sensitivity analysis, the benefit-cost ratio falls below one only when "two or more large adverse circumstances—each considered unlikely—are assumed to occur in concert" [8, p. 1.8–2]. The AEC felt that this result justified its earlier decision to give the breeder highest priority in its reactor development program.

As one might expect with an issue as complex and as politicized as this one has become, the AEC's interpretation of its modeling results were far from universally accepted. Of particular interest from a modeling perspective is that most of the disagreement centered on the appropriateness of specific input assumptions and not upon the AEC's choice of an analytic framework. In fact, critics relied heavily on selected outputs from ALPS in challenging the AEC's conclusions. Thus, along with PIES, this case presents an example of counter or adversary modeling.

BESOM (Brookhaven Energy System Optimization Model). A major criticism of the AEC's projections for nuclear power growth was that they failed to place the projections within the context of the total U.S. energy system. There are many alternative ways to satisfy end-use energy demands. Energy sources compete to serve specific functional demands such as space heat, petrochemicals, and automotive transport. For example, technological change and pricing policies in the electric sector will affect the competition between electricity and gas for space heating. A model that looks only at the electric sector will fail to analyze the potential for interfuel substitution between electric and nonelectric energy forms.

When the Energy Research and Development Administration (ERDA) came into being in 1975, it assumed responsibility for managing and coordinating the entire energy R&D program that had hitherto been fragmented among a number of agencies within the federal government. The Federal Non-Nuclear Energy Research and Development Act of 1974 established ERDA, and required the agency to submit to the Congress an annual plan for energy research, development, and demonstration. To comply with this requirement, a model was needed similar to those employed for optimization of the generating mix within the electric industry, but also with the capability of analyzing the complete energy system including both the electric and nonelectric sectors.

For the preparation of ERDA-48 (its first planning document), ERDA relied heavily on the Brookhaven Energy System Optimization Model (BESOM) [22]. BESOM [35] is similar to ALPS in that it minimizes the total cost of satisfying a given set of energy demands. However, the optimization is performed on the basis of annual cost in a single target year rather than a minimum present worth over some planning horizon. Typically, results are reported for the years 1985 and 2000. This static simplification is probably adequate for the analysis of interfuel substitution. An intertemporal dynamic model is not needed for this range of policy questions. This differs from breeder R&D policy, where the central uncertainties relate to the cumulative exhaustion of uranium resources over time.

BESOM is formulated as a *weighted distribution model* [16, ch. 21]. Given a set of end-use energy requirements and a set of available energy resources and conversion efficiencies, the energy flows throughout the system are calculated so as to minimize total costs subject to the demand and resource constraints in the target year.

Figure 8 illustrates the network format (Reference Energy System) based on a detailed projection of end-use demands for 1985. Each link in this network represents a physical process or a mix of physical processes for a given activity. Each successive step in the supply chain is integrated along with the end-use devices. The *sources* in this problem are identified with primary energy supplies (e.g., underground and strip-mined coal, domestic and imported oil, hydroelectric, nuclear, etc.). *Destinations* are identified with end-use demands (e.g., air conditioning, space heat, petrochemicals, etc.). The costs of extraction, refining and conversion, transportation and storage, and final utilization are assigned to each supply-demand combination.

BESOM has been used to study the competition between electric and nonelectric energy forms in specific end-uses, the feasible range of electrification of the energy system, the break-even costs and the optimal

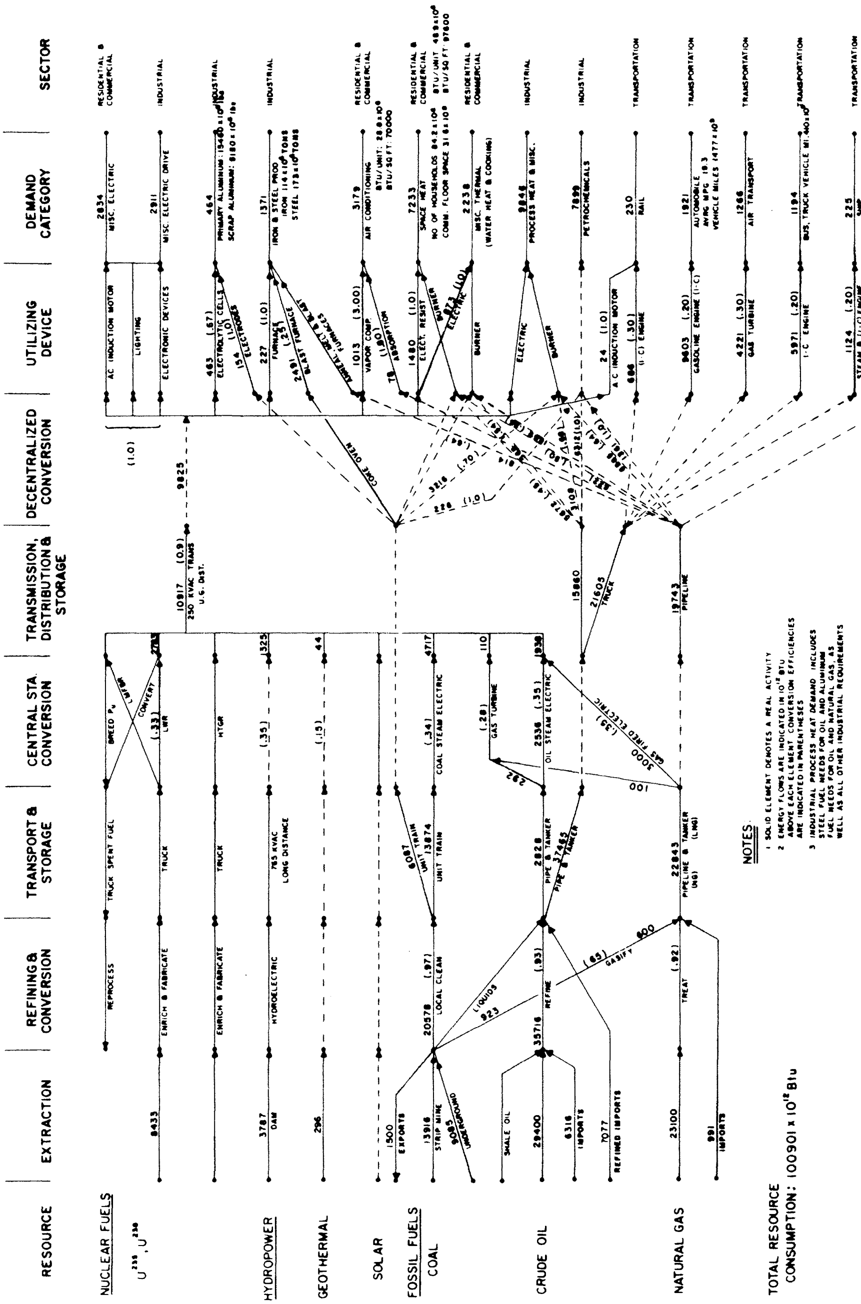

Figure 8. United States reference energy system, year 1985 (source: [35]).

implementation model of new energy technologies. A dynamic, time-phased version of this model has been developed, and is known as DESOM [14]. It incorporates the same technical detail and constraints as BESOM, but treats plant expansion, exhaustible resources, and capital requirements explicitly. Like its static counterpart, DESOM assumes future demands for energy services as given, and then determines the combination of energy resources and technologies to be used over time in order to meet those demands at least cost.

In its review of ERDA-48, the Office of Technology Assessment (OTA) argued that BESOM was biased towards high technology and capital-intensive energy supply alternatives [55]. The criticism was based on the fact that the ERDA scenarios all assumed the same set of final demands. OTA pointed out that in scenarios where the supply system is constrained so that marginal costs rise significantly, these high prices will cause consumers to adjust their demands downward. Moreover, the price increases might be so high that economic growth would be retarded. This would lead to even lower energy demands than would occur as a result of the direct price effects. These issues have led to a series of models dealing with energy-economy interactions. Five of these are reported in [34]. We shall now turn to one representative of this type of analysis.

ETA and ETA-MACRO. These models were designed to overcome the objections to long term demand projections that are independent of supply conditions and prices. The Energy Technology Assessment (ETA) model [47] incorporates both own- and cross-price elasticities for electric and nonelectric energy, and is a partial equilibrium model covering the entire U.S. energy sector. In this way, rising prices for one energy form can be offset by conservation of that fuel and also through substitution by other fuels whose prices have risen less rapidly. (Recall Figure 1 and also the PIES and Kennedy models.)

The demand side of ETA is based upon a hybrid of econometrics and of engineering process analysis. Energy demands are divided into two broad categories of secondary energy forms: *electric* and *nonelectric*, with the energy demand functions providing for a good deal of possible substitutability between energy and other economic inputs. The ease or difficulty of such trade-offs is summarized through a single parameter η, the price elasticity of demand for primary energy.

The supply side of ETA is handled through a conventional linear programming process analysis. Electric energy can be produced by coal-fired power plants, light water reactors, fast breeder reactors and an advanced electric technology (e.g., solar, fusion or an advanced breeder). Nonelectric energy (liquids or gases) may be supplied by oil, natural gas, coal- or shale-based synthetic fuels, or hydrogen via electrolysis.

An intertemporal market equilibrium for the energy sector is approximated through MINOS, a reduced gradient nonlinear optimization algorithm [52]. The objective function may be viewed in either of two logically equivalent ways: (a) maximizing the sum of consumers' plus producers' surplus, or (b) minimizing the sum of conservation plus interfuel substitution plus the costs of energy supply. In either case, costs and benefits are interpreted as *present values*, discounted over a 75-year planning horizon.

ETA has been employed primarily in the nuclear power debate. It was one of several models used by the Modeling Resource Group of the Committee on Nuclear and Alternative Energy Systems (CONAES) to estimate the economic value of new energy technologies [51]. ETA was also employed by the Nuclear Energy Policy Study Group (NEPS) to assess the economic costs of foregoing plutonium reprocessing [43]. The NEPS study has been frequently cited as the analytic basis for the Carter Administration's opposition to plutonium-fueled reactors. In reaching its conclusions, however, NEPS relied heavily on political analyses of nuclear weapons proliferation rather than on environmental, health or economic assessments.

In ETA—as is typical of energy sector models—real GNP growth is projected on the basis of population, labor force and per capita productivity considerations. Total energy demands are then estimated by assuming that they depend on real GNP growth and energy prices. This partial equilibrium approach does not allow for the prospect that rising energy costs and limited supplies will prevent the economy from achieving its full potential GNP growth rate, and that this in turn will slow down future capital accumulation.

Since rising costs and dwindling supplies of energy may have significant macroeconomic implications, several modeling efforts have focused on the general equilibrium links between the energy sector and the rest of the economy. One such effort was nicknamed ETA-MACRO [34, pp. 1–45]. This represents a merger between ETA and a macroeconomic growth model providing for substitution between capital, labor, and energy inputs.

ETA-MACRO simulates a market economy over time, assuming that producers and consumers are sufficiently farsighted to anticipate future scarcities. Supplies, demands and prices are matched through a dynamic, nonlinear programming model. The higher that prices rise, the greater the amount of future supplies that are likely to become available, and the greater the inducements for consumers to conserve energy.

Figure 9 provides an overview of the principal static linkages between the sectoral and the macrosubmodels. Electric and nonelectric energy are supplied by the energy sector to the rest of the economy. Gross output depends upon the inputs of energy, labor and capital. In turn, output is allocated between current consumption, investment in building up the stock of capital and current payments for energy costs.

The macroeconomic production function provides for substitution among the inputs of capital, labor, and energy. The degree of substitutability will affect the economic losses from energy scarcities and price increases. In ETA-MACRO, the ease or difficulty of these trade-offs is summarized through the production function parameter σ, the *elasticity of substitution.* (Recall Figures 2 and 3 above.) By bringing energy directly into the macroeconomic production function and by focusing on energy-economy interactions in terms of a single easily interpreted parameter, ETA-MACRO permits the exploration of those macroeconomic issues that are of particular interest to energy policy and technology assessment. A typical output is shown in Figure 10. This illustrates how certain policies involving the energy sector can lead to a reduction in macroeconomic activity. Here, a limitation on nuclear energy induces conservation. This is costly, however, and leads to a drop in GNP and consumption. The economic consequences of, say, a no nuclear policy may be measured either year-by-year, or else by adding the present value

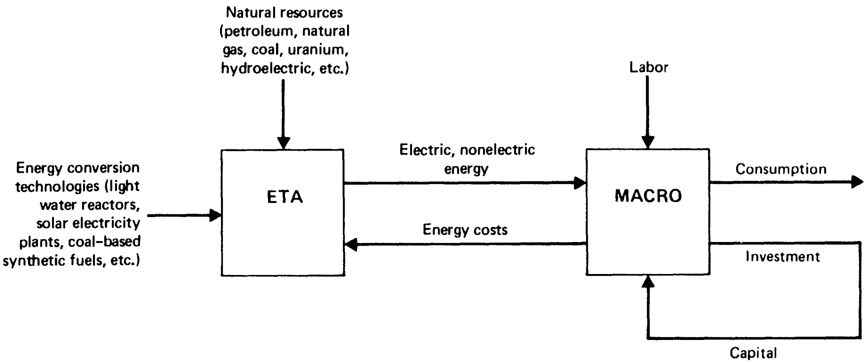

Figure 9. An overview of ETA-MACRO (source: [34]).

of the losses in aggregate consumption over all years from 1975 through 2050. Note that the principal effect of such a policy would not be felt until the 21st century. This has therfore led to an extensive debate over the appropriate rate at which the distant future is to be discounted. (For example, a significant innovation of the CONAES Modeling Resource Group [51] was its use of two discount rates: (1) a pre-tax rate to be used in modeling private investment decisions, and (2) a post-tax rate to be used in discounting the net economic benefits of public R&D. This split discount rule, although a plausible description of the U.S. economy, reminds us that the corporate income tax creates a "second best" situation in which capital equipment investment rates are lower than is socially optimal.) CONAES has also led to a debate over the environmental feasibility of rapid expansion of coal as an alternative to nuclear energy.

4. DECISIONS UNDER UNCERTAINTY

Long term energy planning always entails great uncertainties. Up to this point, we have said little about the treatment of uncertainty. Most energy modelers have relied almost exclusively on deterministic methods, with uncertainty handled through sensitivity analyses. Economic assessments typically contain benefit-cost calculations for a large number of scenarios, with each scenario representing the uncertainties as though they could all be resolved before any actual choices had to be made.

A deterministic model will suffice if the optimal near-term decisions

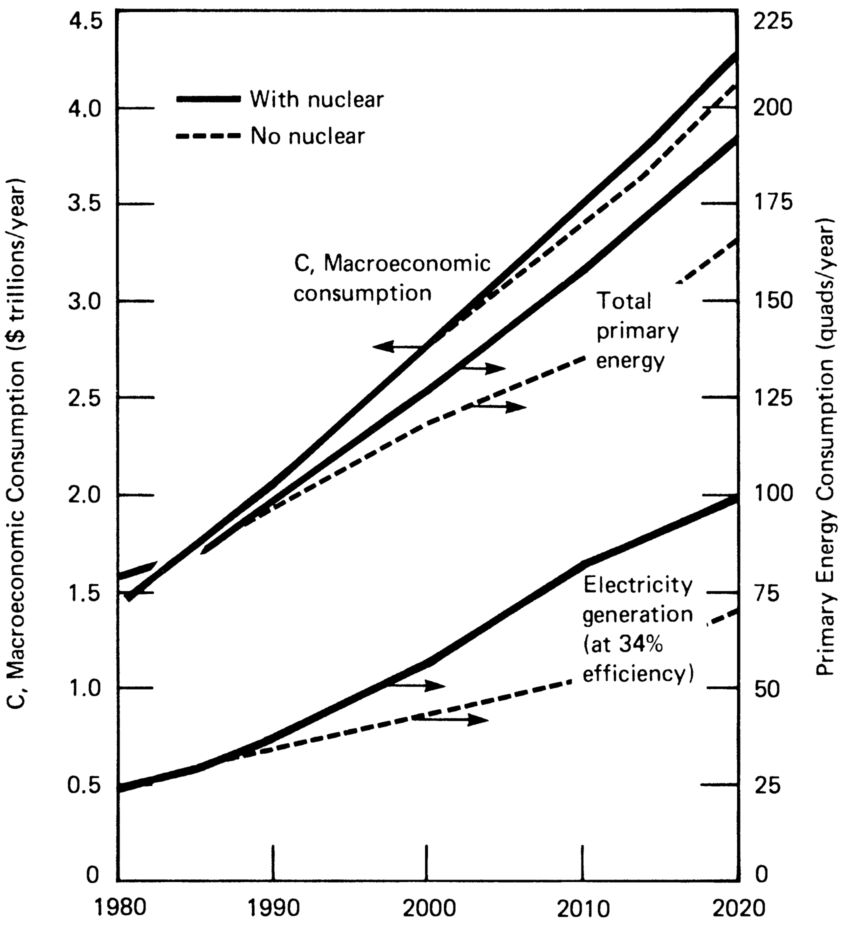

Figure 10. Aggregate results from ETA-MACRO (source: [34]).

turn out to be insensitive to the long term uncertainties. In this case, additional information will be of little value, and a complete course of action can be laid out in advance. If however, the different scenarios imply differences in the optimal initial choice, a deterministic model is an incomplete guide. Decision analysis has proved useful in such situations. Because of its explicit treatment of risk and sequential decisions, this type of analysis is particularly well suited to R&D strategies.

In principle, the approach is straightforward. Using a tree diagram, the analyst graphs the problem as a series of decision and chance nodes unfolding sequentially over time. Through this process, policy makers are led to define a set of feasible alternatives, uncertainties and their possible outcomes. This helps to identify a robust optimal strategy, one that maximizes expected net benefits, allowing both for upside and downside risks.

The methodology is straightforward in principle, but can be difficult to implement. It is not easy to obtain agreement on probability distributions over chance nodes 15 or more years in the future. It requires considerable care to define the set of feasible alternatives. If the problem is to be reduced to manageable and comprehensible dimensions, it becomes necessary to restrict the set of possible outcomes and of feasible alternatives. Tree pruning must be done carefully. It is particularly difficult to avoid bias in the assessment of probabilities.

A synthetic fuels decision analysis. This work is summarized in the report of the Synfuels Interagency Task Force, The Task Force was formed in 1975 to examine alternatives for implementing President Ford's goal of assuring early commercialization of synthetic fuels in the United States [26, 64].

Synthetic fuels would not be competitive at 1975 oil import prices. The net benefits from a synthetic fuels commercialization program are dependent upon the assumed strength of OPEC and thus the future world oil price, the U.S. long range energy supply and demand situation, the future cost of synthetic fuels, and the effectiveness of a synthetic fuels program in reducing costs. The first step in the analysis it to perform a deterministic sensitivity analysis to identify those parameters for which the uncertainties are crucial. The decision tree approach then enables us to design a flexible synfuels development strategy, one that takes advantage of the sequential nature of decisions and of information flows.

The Synfuels Task Force relied on the SRI-Gulf model developed by Cazalet for its deterministic benefit-cost calculations [11]. The model is similar to Brookhaven's DESOM in that it is structured around an energy network containing various energy efficiencies, resource availabilities at particular prices, and capacity contraints associated with specific energy technologies. The SRI-Gulf model contains considerably more regional detail than any of the other long term models described above. It reports end-use data for 9 census regions and output data for 20 supply regions in the United States. Supplies and demands are balanced simultaneously at each node at each point in time over the 50-year planning horizon.

Figure 11 represents a part of this energy network. At each node, the model contains price-responsive functions to estimate the market shares captured by individual technologies. Because of the high degree of regional and process detail, the model has thousands of such nodes, and requires the solution of 100,000 simultaneous nonlinear equations. This is done through a successive approximation algorithm using decomposition techniques.

As a first step in identifying an optimal R&D strategy, the SRI-Gulf model was used to calculate benefits for alternative synfuels development programs. Had the optimal near-term strategy been insensitive to changes in input assumptions, the deterministic model would have provided a good enough approximation. Unfortunately, this did not turn out to be the case. Plausible scenarios were found to support options ranging from a maximum R&D effort to abandoning the entire program.

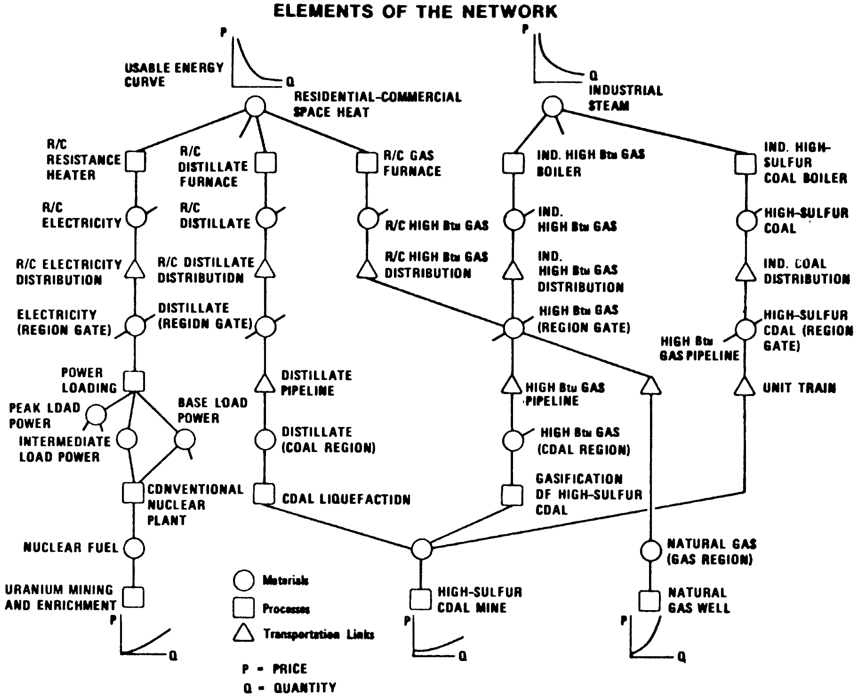

Figure 11. Schematic diagram of the network structure of the SRI-Gulf model (source: [64]).

The problem was then formulated in a decision analysis framework, aggregating the regional and product details for simplicity. Figure 12 presents the synthetic fuels tree diagram. The squares denote decision nodes, and the circles denote chance nodes. The initial decision was reduced to a choice among four alternative government financed synthetic fuel programs:

1. No program—no official commercialization program, but continuation of research and development;
2. Information program—a program designed to produce approxi-

mately 350,000 bbl/day of synthetic fuels by 1985;

3. Medium program—a program designed to produce approximately 1,000,000 bbl/day of synthetic fuels by 1985;
4. Maximum program—a program designed to produce approximately 1,700,000 bbl/day of synthetic fuels by 1985.

These options are represented by the four branches emanating from the first decision node.

The next three nodes denote the improved information that will become available between 1975 and 1985. This information in turn affects private corporate decisions in 1985 on subsequent expansion of the synthetic fuels supply.

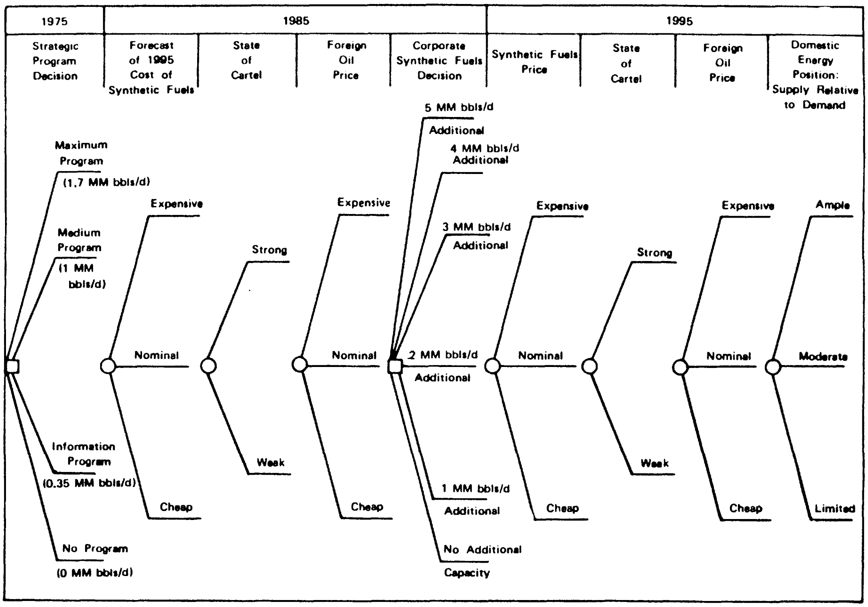

Figure 12. Synthetic fuels decision tree (source [64]).

The first chance node, *1995 Synthetic Fuels Cost*, represents U.S. energy industry beliefs in 1985 regarding the price of synthetic fuels in 1995. Similarly, the *State of Cartel* is defined as the ability of the cartel to influence prices in 1985. The outcome of this uncertainty in turn influences the foreign oil prices. For example, with a strong cartel expensive foreign oil is priced at $19/barrel, whereas with a weak cartel expensive oil costs only $10/barrel.

There are six brances emanating from the down stream decision node, and these represent six expansion alternatives. The corporate cost of this additional capacity depends upon the 1975 public decision as well as on the resolution of uncertainties prior to 1985. The corporate synthetic fuels expansion choice will, in turn, affect the remaining 1995 chance events. At that date, the 1995 synthetic fuels cost is revealed, followed by the state of the cartel and foreign oil prices. The domestic energy position (supply relative to demand) is represented by the final chance node.

Each chance node represents a point where uncertainty will be resolved. Uncertainties are represented numerically through subjective probability distributions incorporating prior hunches, convictions, and information about the likelihood of various states of the world. This is the most controversial aspect of the procedure. Critics say that probability theory cannot be applied to certain types of ignorance, such as the state of the cartel two decades hence. The decision analyst, on the other hand, argues that policy makers can nonetheless scale their hunches about vague but relevant probabilities, and then use these probabilities for policy making. To act otherwise ignores important information.

After considerable interagency debate, the Task Force agreed to a nominal set of judgmental probabilities. Based on these estimates, the optimal initial choice turned out to be *no program*. That is, the expected discounted net benefits of the maximum, medium and information level programs were all negative. A probabilistic sensitivity analysis was also performed to determine how the optimal strategy would depend on the subjective probability about one particular event when all other random variables are taken at their nominal assigned probability values. This gives some measure of the robustness of the optimal strategy. Figure 13, for example, shows the effect of varying the probability of a strong cartel.

The synfuels decision analysis played an important role in the report of the Synfuels Interagency Task Force. Although the *no program* option was ultimately rejected, the analysis is credited with persuading the Administration to cut back from President Ford's original goal of one million barrels down to 350,00 barrels a day by 1985.

A breeder decision analysis. Most breeder benefit-cost analyses have been deficient in their treatment of uncertainty. In its comments on WASH-1535 (the AEC's proposed final environmental impact statement on the breeder), the Environmental Protection Agency (EPA) was critical of this aspect of the analysis.

> Ultimately, the acceptance or rejection of the LMFBR (breeder) program must be based upon a scheme for dealing with uncertainty that surpasses the discussion in the existing benefit cost analysis. The method of dealing with uncertainty should be made explicit in the final benefit cost analysis [8, p. V.84–14].

In the AEC analysis, plausible scenarios were found to support a wide range of alternative choices. Although a base case was identified, it was difficult to evaluate the likelihood of other scenarios and hence the probability that net benefits will be positive or negative.

A closely related aspect is the failure to capture the sequential nature of the problem. From reading WASH-1535, one gets the impression that it is necessary to make a decision now as to when the breeder will be available for commercialization. This is not the case. The decision to be made pertains only to the demonstration phase. Proceeding with this part of the program should not be interpreted as a commitment to an

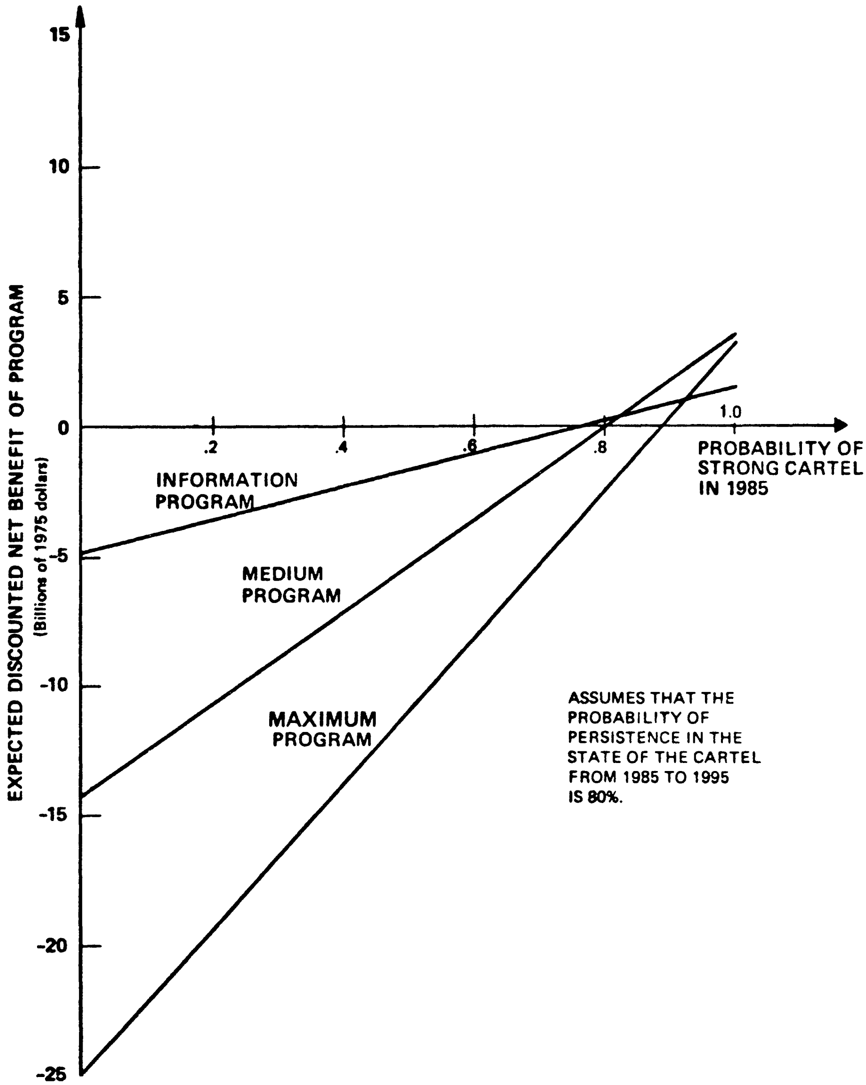

Figure 13. Sensitivity of expected net benefit to the probability of a strong cartel in 1985 (source: [64]).

entire development timetable. The General Accounting Office (GAO) underscored this point in its review of the program.

In considering future alternatives, it is important to recognize that to continue the LMFBR program is a decision to provide additional government resources for the next step in a complex multistep process; it is not an irreversible commitment by the United States to the wide-spread commercial use of LMFBRs [28, p. 85].

An early commitment to an entire development and commercialization timetable is unnecessary. Better information on technical and economic uncertainties should become available as the program proceeds. One should avoid premature elimination of future options which may prove desirable after some of the key uncertainties have been resolved. This type of reasoning has been employed in a decision analysis employing ETA-MACRO to evaluate alternative breeder R&D strategies [48].

Figure 14 presents four breeder R&D strategies: concurrent development, sequential development, wait, or stop. Note that only one path

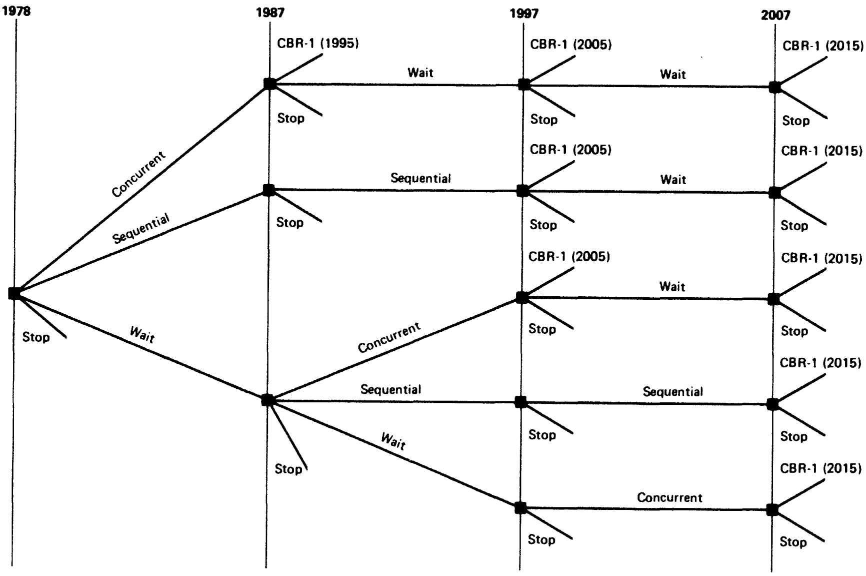

Figure 14. Alternative breeder R&D strategies (source: [48]).

leads to the first commercial breeder reactor (CBR-1) in 1995. This path would require an immediate decision to build a demonstration plant and prototype large breeder reactor concurrently, and then in 1987 a second decision giving the go ahead to CBR-1. With this time sequence, the construction of the prototype would begin before the demonstration plant reached criticality, and construction of CBR-1 would begin before the prototype plant is completed. Hence, the upper path is labeled concurrent development. Note that this path also includes the option in 1987 of delaying CBR-1 from 10 to 20 years.

Table II lists the uncertainties and possible outcomes considered in this analysis. It was assumed that there are only three future dates at which decisions are to be made, and that these future decisions will be based upon the improved information that will be available at that time. A questionnaire was employed to estimate probabilities for the key uncertainties. Two consecutive polls were conducted among members of the Overview Committee of the Committee on Nuclear and Alternative Energy Systems (CONAES).

The respondents differed widely in their individual probability assessments, and so there were substantial differences in their implied evaluations of alternative development strategies. However, based on the probability responses of seven of the eight respondents to the poll, concurrent development would be the optimal economic choice. This would be a

TABLE II

DATES OF RESOLUTION OF KEY UNCERTAINTIES

1987		1997		2007	
Demand	High Reference Low*	Uranium resources	Low Reference High	6 GW solar electric in 2000	2.7 × LWR capital costs 1.25 × LWR capital costs*
Coal and shale constraints	Yes No*				
Cost of nonelectric AES	$8 $5 $2*				
Public acceptance of breeder	Yes No*				

* Event leading to zero gross economic benefits of the breeder, hence negative expected net benefits of a development program. In each of these cases, it is unnecessary to run a detailed gross benefits calculation via ETA-MACRO (source: [48]).

robust strategy despite the differences in individual probability assessments.

Synthetic fuels and the breeder are but two of the many advanced technologies that are under development. Common uncertainties face each of these programs: the size of fuel resources, technological feasibility of alternative supply and conservation options, eventual commercial attractiveness of those options, environmental and social constraints, and future energy demands. Because of its explicit treatment of risk and of sequential acquisition of information, decision analysis provides a more logical tool than those that have been previously employed for long term

R&D assessments. It provides a systematic way to organize the far-reaching debates over energy policy and to move toward consensus.

5. UNRESOLVED ISSUES; DIRECTIONS FOR THE FUTURE

Externalities. This survey has been confined largely to economic and technical issues. The modeling community is just beginning to address the broader social and political aspects—health and environmental effects, safety considerations, and nuclear proliferation—of alternative policies. In the early years of the energy policy debate, this omission did not appear serious. However, as the debate has become more intense and more politicized, the need for explicit consideration of these externalities has become increasingly clear. For example, the breeder's proponents believe that this technology provides the most practical route available to a virtually inexhaustible source of energy. (They note that sustained thermonuclear fusion has not yet passed the threshold of scientific feasibility, and that solar energy is likely to remain more expensive than the breeder as a source of electricity.) To its opponents, however, the breeder represents the ultimate Faustian bargain: an "attractive nuisance" providing not only energy but also an unlimited source of by-product plutonium for weapons proliferation, theft and nuclear terrorism.

Linkages between technoeconomic energy policy models and noneconomic models can increase the utility of both. For example, a multiregion energy and interindustry model (which determines the regional configuration of the electric sector) has been integrated with a diffusion-trajectory model for the study of regional air quality and health impact issues [29, 49]. The decision analysis approach discussed in the previous section represents a more formal framework for integrating economic and non-economic concerns. Multiattribute utility analysis [42] provides a technique for resolving controversies over multiple social objectives.

Market imperfections—cartels, regulation, price controls—are the rule rather than the exception in today's energy markets. Existing energy policy models, on the other hand, rely predominately on the theory of perfectly competitive markets. Only a few systems (PIES, SRI, and Baughman-Joskow) are sufficiently flexible simulators to allow for the possibility of markets in which prices are not necessarily equal to long term marginal costs.

Market penetration rates are a difficult feature in most of these models. This is particularly troublesome in analyzing the competition between nuclear and coal-fired power plants for base-load electricity generation. If discounted cost minimization is the sole criterion, it is typical for a model to predict higher rates of market penetration for nuclear power than are observed in the real world. *Ad hoc* remedies may be provided by constraints on market shares for the newer technologies. To resolve this difficulty, it may be advisable to turn to diffusion models such as those described in [56, 58, 59].

The modeling process. Several investigators have concluded that quantitative modeling is rarely used in the formulation of public policies [9, 27]. Others are more optimistic, but clearly identify a need for increased communication between model builders and model users: "Decision makers need a better understanding of the models, their assumptions, strengths, and limitations, and of why they produce the results they do" [31, p.10]. Encouragingly, there now exist a number of projects concerned with improving the usefulness of energy models in public decision making.

The Electric Power Research Institute has initiated two projects to promote professional standards for energy policy analysis. The Energy Modeling Forum (EMF) project was set up in 1976 at Stanford University to improve the use and usefulness of energy models. Working groups of model builders and users reach agreement on a set of common assumptions, e.g. GNP growth rates, energy costs, etc. With these benchmark assumptions, a number of individual models are then run independently. The results are compared to identify model deficiencies, inconsistencies, and misunderstandings [20, 21]. (A comparative model study involving 6 energy policy models had previously been conducted by the CONAES Modeling Resource Group [51]. PIES, BESOM, and the SRI and ETA models (Sections 2 and 3) as well as the Nordhaus [54] and DRI [19] models were employed by CONAES in this earlier effort.) A "Model Verification and Assessment" project was established at Massachusetts Institute of Technology in 1977. It complements the EMF by going more deeply into the testing and appraisal of individual models. The assessment project has the dual purposes of (1) developing procedures and methodologies for in-depth assessment, and (2) applying these assessment procedures to individual energy models [50].

Through processes of this type, it may be possible to inch our way toward a national consensus on energy policy. Realistically, however, we must recognize how many issues remain unresolved. Environmental, social, and political factors lie well beyond the scope of today's techno-economic models. These externalities have been inadequately handled, primarily because they are poorly understood by the specialists who study them. In view of these limitations, it makes little sense to incorporate such factors formally within large-scale systems analyses. Thus, there remains considerable scope for intuition and informal analysis to complement the logical consistency framework that is imposed by any OR model.

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