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The National Center for the Analysis of Energy Systems (NCAES) at Brookhaven National Laboratory (BNL) has collaborated in the development of an integrated technological and econometric representation of the nation's energy and economic systems(1). Among the applications of this integrated methodology are the assessment of energy-economy interactions, benefit/cost analyses of alternative energy policies, and multi-objective supply and demand studies relating to energy research and development and technological change.

The integrated analytical system is comprised of three component models. The economic growth model included in this framework is the Dale W. Jorgenson Associates (DJA) Long-term Interindustry Transactions Model (LITM)(2). The LITM model provides a flexible, interindustry representation of sectoral production and final demand, and captures the combined influences of productivity, investment, and labor supply on the expansion of U.S. productive capacity over the long-run. The second component of this model system is a detailed technological model of energy supply, conversion and end-use demand. The Time-stepped Energy System Optimization Model (TESOM) developed by Brookhaven National

Laboratory [3] represents the full feasible range of energy resource and technology substitutions for the U.S. energy system. The final component of this model framework is the input-output model developed jointly by Brookhaven National Laboratory and the University of Illinois[4]. This detailed input-output model (I-O) of the structure of the U.S. economy maps the outputs of the conventional energy supply and conversion sectors into nonsubstitutable energy service demands for each interindustry sector and final demand. The combined Brookhaven National Laboratory/Dale W. Jorgenson Associates (BNL/DJA) combined model system provides a comprehensive long-run representation of U.S. energy consumption and energy-economy interactions.

1. THE DJA/LITM MODEL

The DJA Long-term Interindustry Transactions Model is a simulation model of the structure and growth of the U.S. economy. Production and spending throughout the economy are represented on a sectoral basis within a flexible interindustry framework which permits substitution among capital, energy, labor, and materials in the production of goods and services that comprise the gross national product. There are ten producing sectors, of which four are nonenergy and six sectors define energy extraction and processing activities. These sectors are: agriculture, nonfuel mining, and construction; manufacturing; transportation; services, trade and communications; coal mining; crude petroleum; petroleum refining; electric utilities; gas extraction; and gas utilities. In addition there are three other sources of inputs into production (capital, labor, and competitive imports) and four categories of final demand for goods and services (personal consumption expenditures, investment, government purchases, and exports). These economic activities are organized into a matrix of interindustry transactions in which balance or consistency is required. Sectoral output prices must cover average costs of production including a normal rate of return. For each sector, the level of output must exactly equal the quantity of that good or service required for both input to other producing sectors and to satisfy final demand. In addition, prices and quantities must be such that the revenue received by a sector is exactly accounted for by payments to inputs, including income to capital, and by payments to governments. Imports are constrained by the available revenue from exports together with a limitation on the size of the foreign deficit. Finally, the demands for capital and labor inputs must be consistent with the supplies of these resources.

Economic activity patterns within the LITM framework are represented by econometric submodels for consumption and for each producing sector which incorporate the patterns of technical and behavioral responses observed for these activities, as based on econometrically estimated interrelationships from a data base spanning the years 1947 through 1972. This approach gives a flexible and consistent representation of economic behavior. The submodels provide a framework for the analysis of output price formation and, thus, determine the system of relative prices characterizing the economy. These submodels also determine the cost minimizing pattern of input purchases given prevailing prices. Therefore, the input-output coefficients are endogenously determined as functions of relative prices. Similarly the pattern of consumption spending is modeled in a flexible manner. The LITM framework provides for the incorporation of substitution or complementary relationships between inputs and adjustments in the pattern of final demand expenditures.

The LITM model is a dynamic equilibrium model of the U.S. economy. For each of the commodities endogenous to the model, an algorithm of price formation based on the balance between demand and supply determines relative prices. Equivalently, the pattern of economic activity in each year is consistent with these prices as determined by the observed patterns of substitution and other responses by producers and consumers. In addition, the model includes a balance between saving and investment that determines the rate of return and the rate of growth of the capital stock. Economic growth is modeled as a sequence of one-period equilibria determining demand and supply and relative prices for all commodities. Investment in each period determines the level of capital stock available in the following period. Dynamic adjustment to energy changes is modeled by tracing through the impact on future levels of capital stock and the rates of change of factor productivities. The LITM model provides a consistent framework for analyzing the effects of economic changes on the energy system and the effects of energy changes on the structure and growth of the U.S. economy. The economic flows in the LITM model are shown in Figure 1.

2. THE BNL/TESOM MODEL

The Brookhaven Time-stepped Energy System Optimization Model (TESOM) is a national energy system model that was developed for the quantitative evaluation of energy technologies and policies within a systems framework. TESOM is designed to examine interfuel substitution in the context of constraints on availability of competing resources and technologies and their associated costs. The model is formulated as a linear program and is based on the Brookhaven Reference Energy System (RES). The RES provides a complete and consistent accounting system in physical units for energy flows from the extraction or importation of primary energy resources, through refining and conversion, transportation, distribution and storage, to the final consumption of fuels and electricity by end-use technologies for each energy service demand. The comprehensive technological structure in TESOM relates energy flows to the relatively nonsubstitutable energy services such as space conditioning, motive power, and process heating. The RES framework reflects the full feasible range of interfuel and technological substitutability. Figure 2 is a simplified Reference Energy System which represents energy flows in the TESOM model.

The time-stepped model optimally allocates energy resources and products and selects the optimal mix of supply, conversion, and

Figure 1

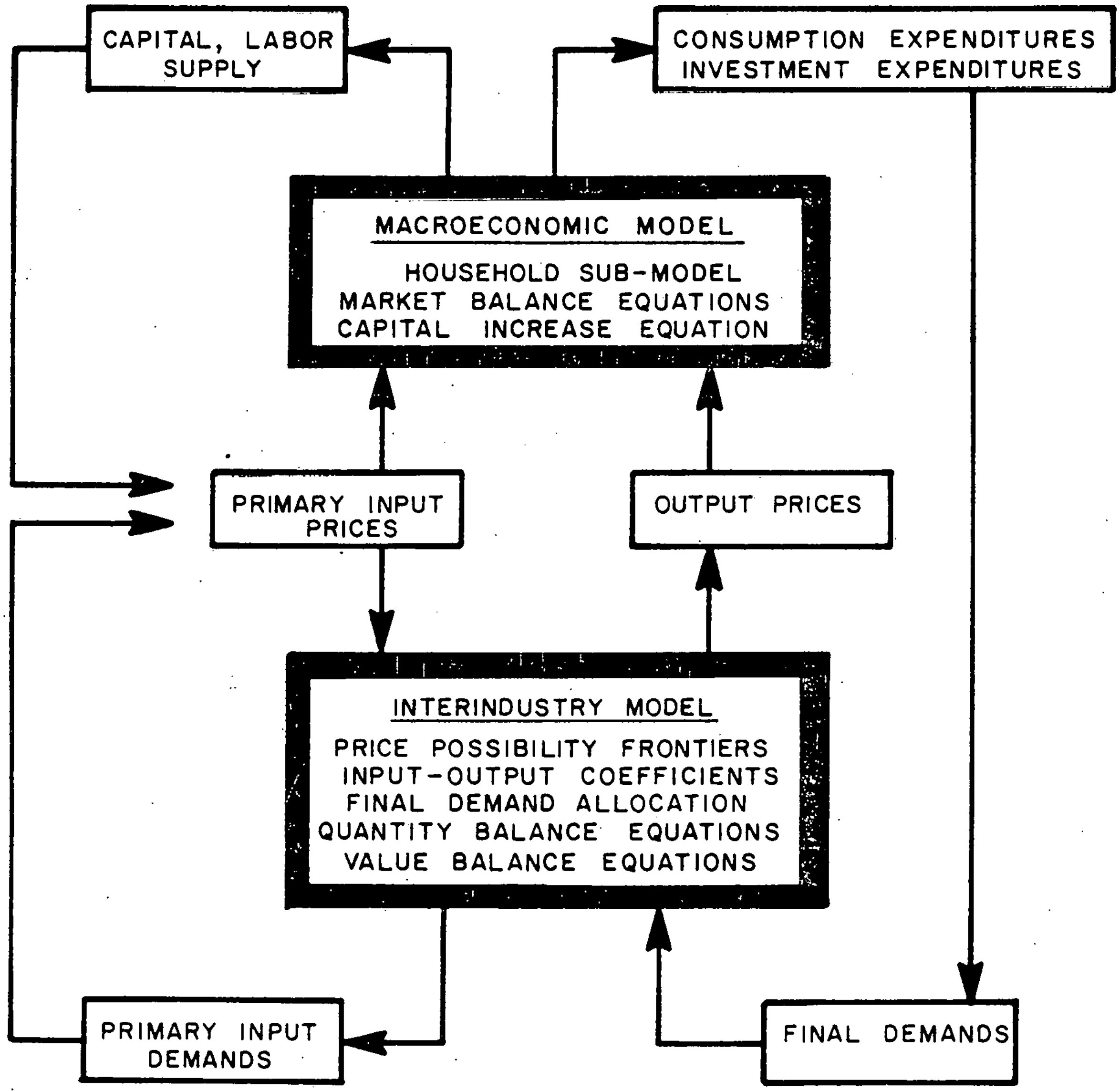
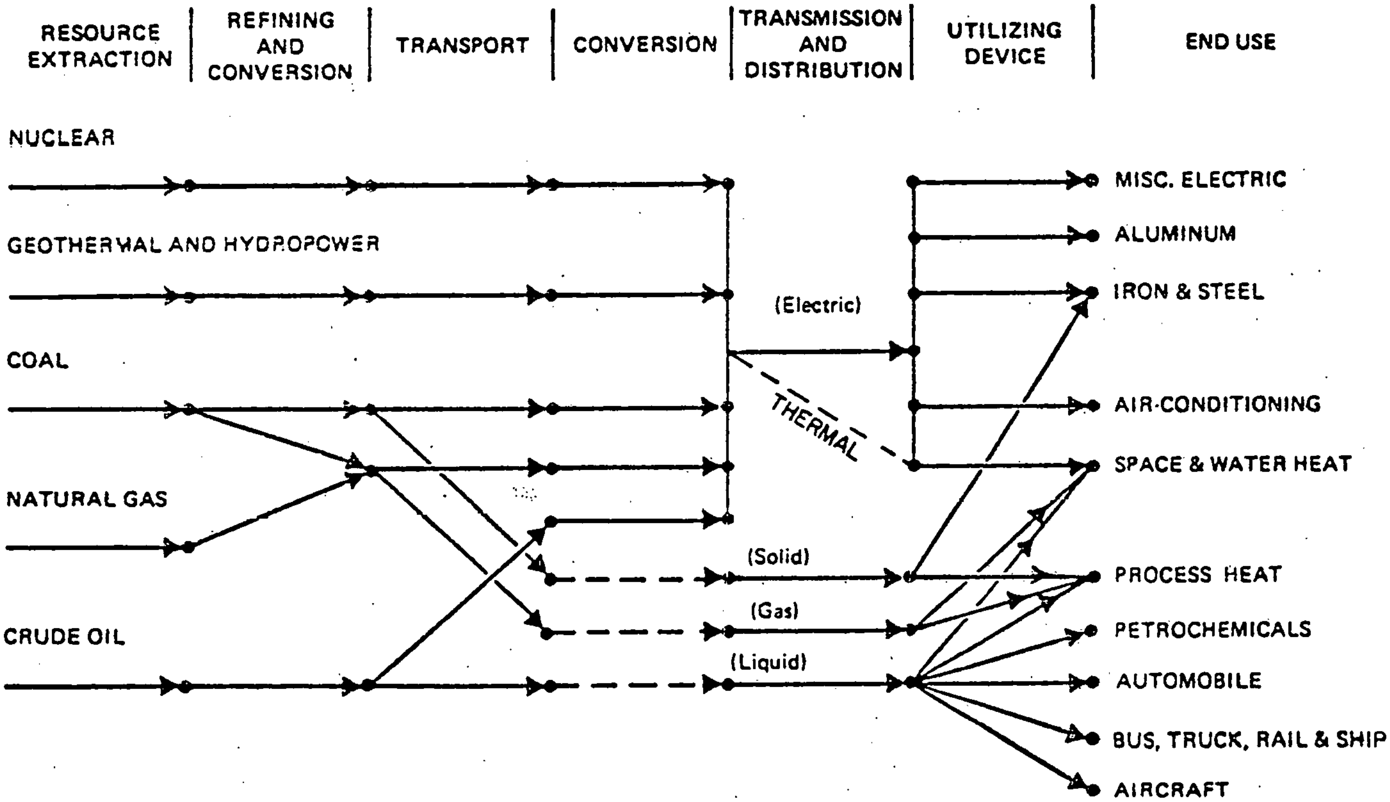

CAPITAL, LABOR SUPPLY
CONSUMPTION EXPENDITURES
INVESTMENT EXPENDITURES
MACROECONOMIC MODEL
HOUSEHOLD SUB-MODEL
MARKET BALANCE EQUATIONS
CAPITAL INCREASE EQUATION
PRIMARY INPUT PRICES
OUTPUT PRICES
INTERINDUSTRY MODEL
PRICE POSSIBILITY FRONTIERS
INPUT-OUTPUT COEFFICIENTS
FINAL DEMAND ALLOCATION
QUANTITY BALANCE EQUATIONS
VALUE BALANCE EQUATIONS
PRIMARY INPUT DEMANDS
FINAL DEMANDS

FIGURE 2


RESOURCE EXTRACTION
REFINING AND CONVERSION
TRANSPORT
CONVERSION
TRANSMISSION AND DISTRIBUTION
UTILIZING DEVICE
END USE
NUCLEAR
GEOTHERMAL AND HYDROPOWER
COAL
NATURAL GAS
CRUDE OIL
(Electric)
THERMAL
(Solid)
(Gas)
(Liquid)
MISC. ELECTRIC
ALUMINUM
IRON & STEEL
AIR-CONDITIONING
SPACE & WATER HEAT
PROCESS HEAT
PETROCHEMICALS
AUTOMOBILE
BUS, TRUCK, RAIL & SHIP
AIRCRAFT

demand technologies according to least cost or other selected energy, environmental, or economic criteria to satisfy a specified set of energy service demands. Resource supply representations are specified as either supply curves or fixed prices and availabilities by year. The TESOM model provides a "vintage" representation of the nation's energy system. The optimal levels of the decision variables for any time period are determined from: the optimal levels established for previous periods; the retirement and deterioration rates, lifetimes and costs of vintage capital stocks; and the economic and technological factors that affect the feasible levels of decision variables for the time period under investigation.

Mathematically, the model is formulated as a sequence of expanded linear programming formulations of the RES--one for each time period. For a given time period, the solutions derived for earlier periods along with assumptions regarding retirement and decline rates, average lifetimes, age-dependent conversion efficiencies, plant factors, O&M costs, and the capital charges for stocks-in-place are incorporated into the sequenced formulation. Under minimum cost or other quantifiable criteria, the energy demands are satisfied in accordance with the supply expansions and increased penetrations that are attainable for the period and the net availabilities from the evolution of the energy system to date.

The electric sector has a unique representation in the TESOM model. Required generating capacity is endogenously determined as a function of the exogenously defined electric demand types such as base and intermediate loads, off-peak, heating and cooling demands. Each demand type has characteristics regarding stochastic behavior, seasonal, and daily loading. By loading the electric energy service demands onto the appropriate demand type, and subsequently loading these onto the various season-day combinations, the height of the total peak demand for each season-day is determined. Required electric capacity is, therefore, the maximum of the individual season-day peaks with allowances for transmission and distribution losses and reserve margins. Load management considerations are introduced explicitly into the TESOM problem formulation, as the load duration curve is determined, in part, from the exogenously specified set of energy service demands and their characteristics.

A mechanism for pricing and adjusting the availabilities of vintage capital stocks, and a market penetration algorithm also are incorporated in the TESOM model in order to smooth intertemporal transitions. These features provide mechanisms for avoiding the "flip flop" characteristic of linear programming models. Vintage capital stocks which are not beyond their economic lifetime impose an annualized capital charge on the system. Thus, fixed costs associated with previous investments are incurred irrespective of whether or not it is optimal to operate, partially or fully, an older technology. "Unrealistic" displacements of relatively inefficient vintages are discouraged when the associated variable costs of alternative stocks are combined with the fact that immediate write-offs are precluded.

The market penetration algorithm requires as input the "optimistic" penetration levels of each technology in each year. These user-specified bounds are then adjusted endogenously to account for the previous penetration and attractiveness of the technology. The penetration algorithm incorporates the marginal values, implementation rates, and lag times from previous periods as well as the technological and market characteristics for the current period into the determination of realistic bounds for each technology.

TESOM may be used in either an optimization or a simulation mode. In the optimization mode, TESOM calculates the optimal supply-demand configuration of the energy system consistent with exogenously specified constraints such as limits on the availability of resources, market penetration rates for technologies and electric generation capacities. As a simulation framework, TESOM is used to analyze system costs or environmental impacts. Environmental emissions and costs are associated with each of the processes along the trajectory from primary resource supply to end-use demand. The total impacts for each activity are calculated and summed up along each point in the energy system network. Therefore, the TESOM model can be constrained to duplicate a desired supply-demand system and then calculate costs and other quantifiable impacts for that system.

3. THE TESOM/LITM INTEGRATION

The BNL/TESOM and DJA/LITM models are coupled so that in each year there is consistency between the energy and economic information obtainable from each model. This coupling is achieved through an iterative process in which the principal points of interaction are:

- the economic activities of each sector and the aggregate energy inputs to the producing sectors, household sectors, and other final demands;
- The relationship between the aggregate energy inputs to the producing and consuming sectors and the levels of the non-substitutable, functional energy services;
- The details of energy prices, technology production functions, quantities, imports, and the levels of new and conventional energy technologies;
- The relationship among the energy sector details, aggregate energy and nonenergy input substitutions, product substitutions and compositional changes in final demand and the growth of the economy from both demand and supply points of view.

The two models interface at the point of energy demand, with LITM linking aggregate energy demand to the general economy and with TESOM linking primary resources to energy demand. The linked system extends the coverage and applicability of each model and provides a framework for the consistent analysis of the role of energy technologies, energy supply and conservation, energy-economy interactions, and economic effects.

The model coupling operates through several stages. Initially, average supply price indices are projected using, as weights, the energy quantities from a previous BNL/DJA reference projection. The price changes from the reference projection are related to price-quantity elasticities of demand to yield initial estimates of primary energy consumption and, through average system efficiencies, the corresponding levels of energy service demands. These elasticities summarize the equilibrated degree of responsiveness of energy quantity changes to energy price changes from previous solutions of the combined system. TESOM is then solved, constrained by the supply and conversion limitations and subject to the satisfaction of these initially determined levels of energy services.

The solution values of energy prices, technology production functions, quantities, imports, and the levels of new energy technologies from TESOM are entered into the LITM model which is solved to yield estimates of the level and composition of production and spending throughout the economy. Economic sector outputs and the energy input per unit of output are transformed into a restructured set of demands for energy services in physical units. This mapping occurs through a "reduced form" version of the BNL/University of Illinois Input-Output MOdel. Mathematically, these adjustments to the level and structure of energy service demands are determined by accounting for changes in service levels due to changes in the level and structure of economic activity and changes in the energy requirements per dollar of output or consumption for each sector. These account for the substitution of nonenergy inputs in production and consumption.

The final adjustment in the mapping process accounts for changes in demand levels resulting from efficiency improvements from the reference case for each service category. The resultant vector of energy service demands reflects changes in energy prices, the level and composition of economic activity, energy and nonenergy input substitutions in production, and energy system efficiencies. These energy demands are inserted into TESOM and produce a new simulation of the configuration of the energy system. This iterative procedure continues until consistency between the energy and economic systems in the two models is attained. An overview of the structure of the integrated BNL/DJA combined model system is presented in Figure 3.

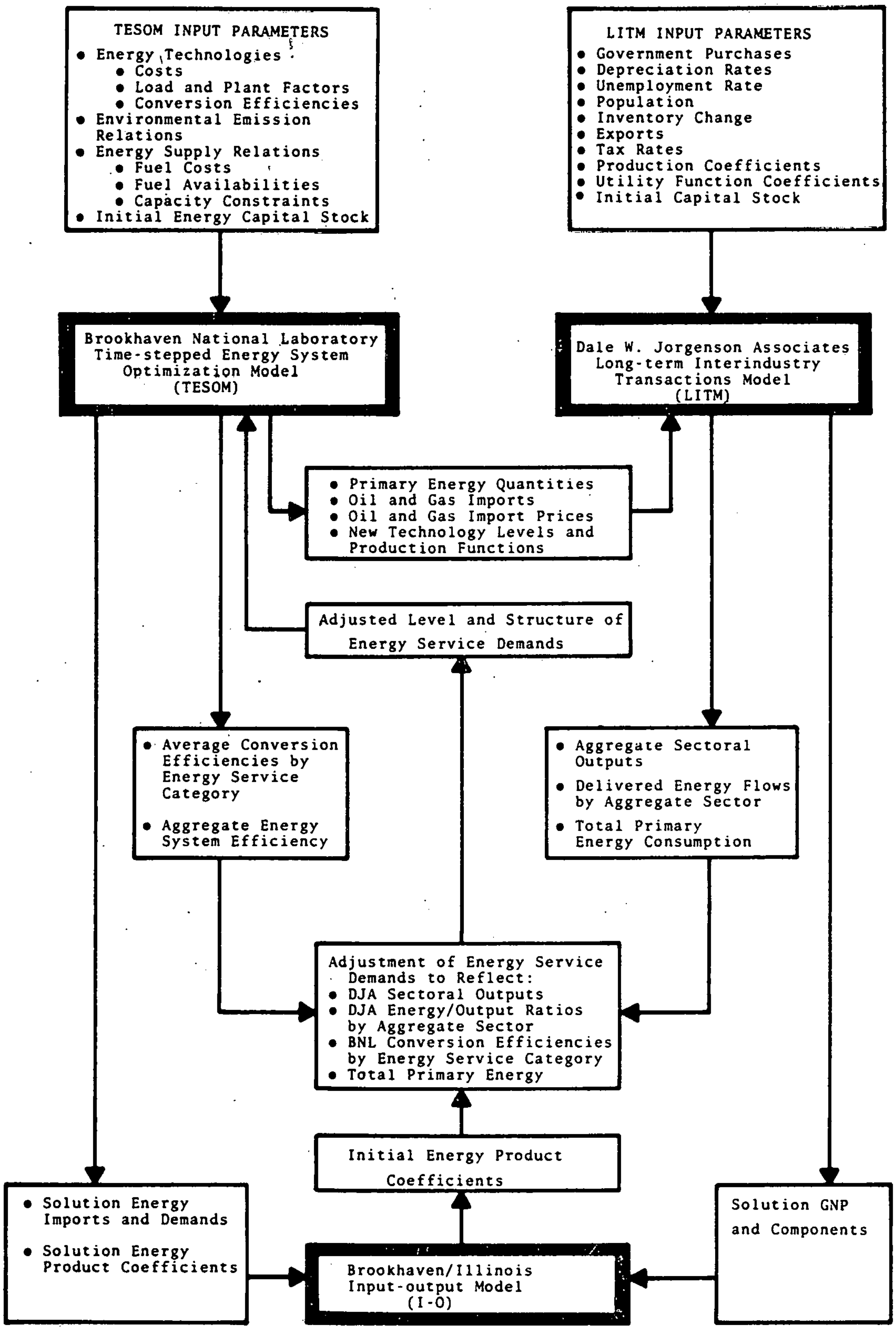
4. THE BNL I-O MODEL

Once a consistent TESOM/LITM solution is achieved, the BNL Input-Output model is run. In contrast to conventional interindustry input-output models, the BNL model is composed of twenty energy and ninety nonenergy sectors with the output of the energy sectors specified in terms of physical Btu units instead of dollar values. This permits direct linkage with the BNL energy process model, TESOM, and provides variable energy coefficients as determined by the solution of the TESOM model. The nonenergy sector outputs are expressed in constant dollar values. Outputs of the energy supply/conversion sectors are distributed to energy service sectors instead of directly to consuming sectors. The supply sectors convert and distribute raw fuels to sectors producing traditional energy forms such as electricity and refined petroleum products, but they allow for nontraditional patterns such as refined petroleum products from coal.

This structure results in the specification of transactions in terms of fuels and end uses. The energy product sectors define eight nonsubstitutable end-use demands for energy: motive power, petrochemical feedstocks, coke, process heat, water heat, space heat, air conditioning, and electric power.

In order to align the BNL I-O model to the TESOM/LITM combined system solution, aggregate nonenergy final demands from LITM serve as control totals for the nonenergy final demands in the input-output model. The energy final demands are provided by TESOM in the form of energy services specified in physical units. In addition, the technical coefficients representing the energy supply to energy product conversions are derived from the TESOM solution. This depicts, for example, energy supply substitution resulting from specific policy assumptions. The input-output model is then solved yielding the detailed output requirements of the economy.

FIGURE 3


TESOM INPUT PARAMETERS
• Energy Technologies
• Costs
• Load and Plant Factors
• Conversion Efficiencies
• Environmental Emission Relations
• Energy Supply Relations
• Fuel Costs
• Fuel Availabilities
• Capacity Constraints
• Initial Energy Capital Stock
LITM INPUT PARAMETERS
• Government Purchases
• Depreciation Rates
• Unemployment Rate
• Population
• Inventory Change
• Exports
• Tax Rates
• Production Coefficients
• Utility Function Coefficients
• Initial Capital Stock
Brookhaven National Laboratory Time-stepped Energy System Optimization Model (TESOM)
Dale W. Jorgenson Associates Long-term Interindustry Transactions Model (LITM)
• Primary Energy Quantities
• Oil and Gas Imports
• Oil and Gas Import Prices
• New Technology Levels and Production Functions
Adjusted Level and Structure of Energy Service Demands
• Average Conversion Efficiencies by Energy Service Category
• Aggregate Energy System Efficiency
• Aggregate Sectoral Outputs
• Delivered Energy Flows by Aggregate Sector
• Total Primary Energy Consumption
Adjustment of Energy Service Demands to Reflect:
• DJA Sectoral Outputs
• DJA Energy/Output Ratios by Aggregate Sector
• BNL Conversion Efficiencies by Energy Service Category
• Total Primary Energy
Initial Energy Product Coefficients
• Solution Energy Imports and Demands
• Solution Energy Product Coefficients
Solution GNP and Components
Brookhaven/Illinois Input-output Model (I-O)

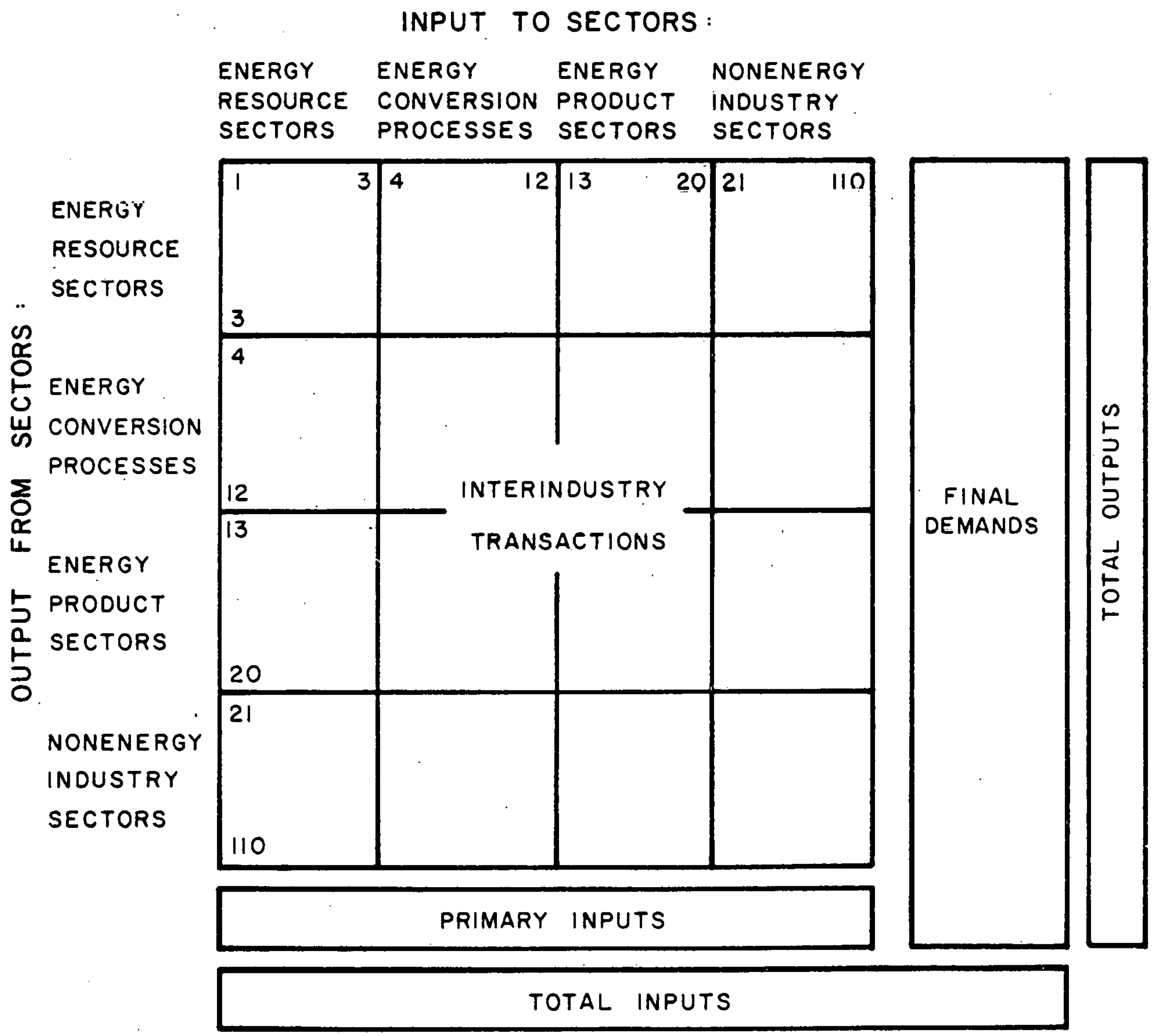
The interindustry structure of the BNL input-output transactions matrix provides a significant degree of disaggregation and permits detailed sectoral analysis within the context of the national economy. The transactions formulation of the I-O model is presented in Figure 4.

5. CONCLUSION

The BNL/DJA combined energy-economic model framework is useful in assessing a broad range of energy policies. The detailed engineering information contained in the TESOM model allows for the evaluation of economic impacts resulting from the introduction of new technologies in the energy system. Changes in income, the levels and structure of production and employment, and prices for both energy and nonenergy goods and services are determined within a consistent framework.

The integrated model system has been used to examine the long-run economic, energy and environmental effects of several energy policies including: oil import reduction policies, moratoria on nuclear generation capacity, and accelerated research and development programs for solar and other renewable resources. The combined model framework is useful to decisionmakers in the Department of Energy in determining optimum allocation of research and development funds among new technology areas, and in measuring the impacts of government imposed conservation standards or energy taxes in the development of a national energy policy. In addition to the wide range of policy issues that can be considered with the BNL/DJA combined model system, each policy can be examined with respect to multiple criteria including economic impacts, effects on national security, energy sector cost minimization, or environmental considerations.

Figure 4


INPUT TO SECTORS:
ENERGY RESOURCE SECTORS
ENERGY CONVERSION PROCESSES
ENERGY PRODUCT SECTORS
NONENERGY INDUSTRY SECTORS
OUTPUT FROM SECTORS:
ENERGY RESOURCE SECTORS
ENERGY CONVERSION PROCESSES
ENERGY PRODUCT SECTORS
NONENERGY INDUSTRY SECTORS
1
3
4
12
13
20
21
110
INTERINDUSTRY TRANSACTIONS
FINAL DEMANDS
TOTAL OUTPUTS
PRIMARY INPUTS
TOTAL INPUTS

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List of Figures