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A CRITICAL REVIEW OF SINGLE FUEL
AND INTERFUEL SUBSTITUTION RESIDENTIAL
ENERGY DEMAND MODELS

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ABSTRACT

The overall purpose of this paper is to formulate a model of residential energy demand that adequately analyzes all aspects of residential consumer energy demand behavior and properly treats the penetration of new technologies, particularly solar photovoltaics, in an explicit fashion. An adequate treatment of energy demand must take account of the fact that both fuel demand and the demand for fuel-burning equipment are jointly derived from the demand for fuel related services. This requires modelling both demand for fuels and for their related equipment. In order to model the equipment demand and the demand for new technologies, the technological characteristics of the alternative equipment must be explicitly analyzed. The formulated model attempts such explicit analyses.

In order to formulate such a model this paper first introduces and reviews 19 existing residential energy demand models to ascertain how well they have dealt with these issues.

PREFACE

The research discussed in this paper reflects work undertaken by the author as part of a larger analysis of the potential markets for solar photovoltaics. That larger analysis has been and is being conducted by the MIT Energy Laboratory for the Department of Energy, formerly the Energy Research and Development Administration.

The author would like to express gratitude for the extremely helpful suggestions of David Wood and Richard Tabors.

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A) INTRODUCTION AND SUMMARY

The activity of critically reviewing a group of positive or normative models of the social or physical sciences can be a thankless task for several reasons. In the first place, the process of model review usually takes the approach of constructive criticism; as a result, while aimed at being constructive, the criticism is still criticism and can affront those modellers whose models are reviewed. In the second place, the review function perforce limits the body of models discussed to those felt to be most relevant to the particular purposes at hand; as a result, the review can also affront those who feel certain crucial or seminal efforts have been excluded.

In spite of these potential difficulties, I attempt to identify and critically review a group of energy demand models in this paper for two major objectives.

1) The first objective is to indicate how various analysts have understood and modelled the demand for energy by residential users. Since the demand for energy is a derived demand given the demand for the services that a given energy source provides (such as heating, cooking, and clothes drying for residential consumers), the analysis of energy demand must deal with the fact that fuels and fuel burning appliances are combined in varying ways to produce a particular residential (and commercial and industrial) service. As a result, analysis of the demand for energy must include analysis of the interactive demands for both fuel burning capital and the fuel used by that capital stock. This review of energy demand models will assess how and how well the reviewed models deal with both of these demands.

2) This review is performed for the Department of Energy in order to develop improved energy demand models for the analysis of the penetration of new energy technologies, in particular solar photovoltaic installations for residential

use. As a result a second objective of the review is to identify the analytic strengths and weaknesses of the assembled models with respect to their usefulness in explicitly analyzing the demand for new energy technologies.

The literature provides a wide array of models available for this review. Over the past ten to fifteen years, quantitative models of the system of sources and uses of various energy forms have come to dominate an increasing share of the engineering, management research, and economic literature. The literature now abounds with old and new models of supply and demand, with characterizations and assessments of new technologies. The research area has been legitimized by a number of review articles such as Hoffman and Wood (50) and Charles River Associates (25).

These models have been developed in order to understand, quantify and finally to predict technological, sociological, and/or economic behavior and relationships underlying an energy system. The desires to understand, quantify, and predict have, at times, been stimulated by academic interest. At other times, the modelling efforts have been intended either to do or to evaluate strategic planning activities and policy analysis. For example, state, local and federal regulatory bodies (FPC, ERDA, FEA, state utility commissions, EPA, CEQ, etc.) affect utility rate structures, environmental compliance costs, research and development into a diffusion of new technologies, pipeline and utility siting, and appliance efficiency standards and taxes, to name just a few. At times the policy planning of these agencies is based upon ad hoc decisions; in other cases, the quantitative models are utilized to help refine and understand the impacts of proposed policy measures (see 58, 34, 63, 44). Likewise, quantitative models have been utilized to do or to evaluate strategic planning for energy industries or other private sector participants (21).

A number of techniques have been utilized in the construction of these energy models including optimizing techniques (linear, non-linear and integer programming - 27, 18), activity analysis and input-output analysis (59, 48, 72), statistical and econometric techniques and engineering/process methods (10, 58, 49). Many models or analyses utilize only one of these techniques; however, others combine several of the techniques.

As indicated above, it is the purpose of this paper to review those models that focus upon the residential/commercial sectors. All the models deal with energy demand; the review will indicate how well the models deal with new technologies and the fundamental fact that the demand for energy related services involves demand for fuels and fuel burning equipment.

The demand models to be reviewed can be divided into two groups:

- models dealing with demand for a single fuel
- models dealing with overall energy demand and interfuel substitution

The models that are reviewed in these categories are listed in Table 1.

While this table contains 19 modelling efforts (enough for any review), the list is clearly not exhaustive. For example, the translog utility analyses of consumer demand characterized by the efforts of Christensen, Jorgenson and Lau and Berndt, Darrough and Diewert¹ are not included. The reasons for their exclusion become clear when the proposed model respecifications are discussed in Section E.

The single fuel demand models analyze the demand for one fuel, usually electricity. In general, the single fuel demand models are more refined in their

¹ See E.R. Berndt, M.N. Darrough and W.E. Diewert (1977) "Flexible Functional Forms and Expenditure Distributions: An Application to Canadian Consumer Demand Functions," International Economic Review, (October, 1977) and Christensen, L.K., Jorgenson, D.W., and Lau, L.J., "Transcendental Logarithmic Utility Function," The American Economic Review, Vol. 65, #3 (June 1975) pp. 367-383.

TABLE 1: MODELS REVIEWED IN SECTIONS C AND D

SINGLE FUEL MODELS

Acton, Mitchell and Mowill
(1976), (AMM)

Anderson (1972), (1973)

Balestra (1967)

Cargill and Meyer (1971), (CM)

Fisher and Kaysen (1962), (FK)

Griffin (1974)

Halvorsen (1973)

Houthakker (1951)

Houthakker, Verleger, Sheehan
(1974), (HVS)

Mount, Chapman and Tyrrell
(1973), (MCT)

Mount and Chapman (1974), (MC)

Taylor, Blattenberger, Verleger/
DRI (1977), (TBV)

Willis (1977)

Wilson (1971)

INTERFUEL SUBSTITUTION MODELS

Baughman/Joskow (B/J)

Federal Energy Administration
Project Independence Evaluation
System (FEA/PIES)

Oak Ridge/Hirst, et al.
(OR/H)

Anderson

Erickson, Spann and Ciliano
(ESC)

analytic structure and data base. For example, Mount, Chapman and Tyrrell (MCT) incorporate variable elasticities that change with the level of the explanatory variables. Acton, Mitchell and Mowill (AMM) and Fisher and Kaysen (FK) utilize a multi-equation specification of demand focusing upon the demand for fuel-burning capital and a separate specification for the demand for a fuel given that fuel-burning capital. The Taylor, Blattenberger, Verleger/DRI (TBV) analysis of residential electricity demand develops marginal and fixed electricity charges.

In spite of their refinement these single fuel models deal inadequately with the competition from other fuels and from new technologies-through price cross-elasticities only. The models dealing with interfuel substitution explicitly are theoretically superior because they are based upon the premise that the demand for any fuel cannot be adequately assessed without quantifying the price and non-price competition to that fuel posed by all alternative fuels and their respective fuel-burning appliances. However, in spite of the theoretical superiority of these interfuel substitution models, the empirical implementation of them has been deficient to date. The analytic refinement and data base development of the single fuel models are missing in the interfuel substitution models. For the most part, interfuel comparisons are based only upon operating costs (2,3,4,5,6,9,10,12,58, 13,35), while the capital costs and technological characteristics of alternative fuel burning devices have been ignored (except in 60 and 45).

These characteristics of the single fuel and interfuel substitution demand models will be explored in greater detail in the actual review sections C and D below. Based upon that review, one must conclude that in spite of the theoretical superiority of the interfuel substitution models, and in spite of the fact that the single fuel demand analyses provide great analytic refinement, extended efforts are still required. The entire generation of energy demand models in the literature have reached a stage of forced obsolescence. New work done on consumer

choice modeling (generalized logit [Hartman (43)] and covariance probit [Hausman and Wise (47)], production/cost duality [Econometrica International (33)], and the explicit differences between short-run and long-run energy demand [DRI (29)] provides extremely cogent arguments for completely respecifying the analyses of energy demand in order to adequately model the penetration of new technologies such as solar photovoltaics within a well specified demand model.

Such a respecification is currently being performed by the MIT Energy Lab for the Department of Energy. The goals of the respecification are based directly on model characteristics explored in the critical review in sections C and D. That respecification is outlined heuristically in Section E. To summarize, that respecification will include the following objectives:

- Explicit dichotomization of the behavioral characteristics and policy variables for short-run and long-run demand.

It was stated above that the demand for energy related services articulates itself in demand for fuels and fuel-burning equipment. The different behavioral characteristics of demands for fuels and for equipment must be properly incorporated. In the short-run, the characteristics and size of the energy-burning capital stock are fixed. Behavioral specifications and policy variables must take into account that demand responses can only take the form of conservation and altered capital utilization. In the long-run, when the size and characteristics of the capital stock are variable, the characteristics of new technologies and interfuel substitution (through changes in the capital mix) become relevant. Likewise in the long-run, appliance efficiency taxes and standards, and appliance capital costs become relevant policy variables in addition to the standard operating costs of the fuels.

- Utilization of appropriate models and data for consumer choice.

Conditional logit has been utilized extensively for the analysis of inter-fuel substitution in a partial adjustment framework. However, conditional logit as used in the literature suffers from a number of difficulties including: the imposition of constant cross-elasticities [see Baughman and Joskow (9, 11, 12, 13), Hausman (46), Domencich and McFadden (32), Hartman (43), and Hartman and Hollyer (45)]; implied misspecification [Hartman and Hollyer (45) and Hartman (43)]; excluded variables; and the restrictive underlying model of individual choice [Hartman (43) and Hartman and Hollyer (45)]. Such modeling of consumer choice could be improved by generalized logit formulations [Hartman (43)] or covariance probit formulations [Hausman and Wise (47)]. Furthermore the choice methodologies could be applied to changes in the appliance stock rather than the actual stock [see Hartman and Hollyer (45)].

- Appropriate treatment of new technologies.

While generalized logit and covariance probit avoid some of the difficulties inherent in conditional logit, the treatment of new technologies is not trivial for either new alternative and careful formulation is required.

The discussion in this review proceeds as follows. Because the purpose of the discussion is to critically review the energy demand models identified in Table 1, Section B introduces a number of model criteria to assist in that review. Utilizing those criteria Section C reviews the demand analyses that focus upon individual fuels and Section D reviews the interfuel substitution models. Finally, Section E summarizes the model evaluation and proposes the nature and scope of model reformulation desirable for better treatment of new technologies (solar photovoltaics in particular).

B) MODEL CRITERIA

The purpose of the model review is to evaluate the models in Table 1, their treatment of demand, and their ability to assess new technologies. Such an evaluation requires some formulation, explicit or implicit, of criteria with which the models can be judged. It is the purpose of this section to introduce a set of such criteria.

Eight criteria for the evaluation of modelling energy demand are introduced and discussed here. The criteria are generally stated; specific articulation for the actual models is found in Sections C and D. These criteria can be utilized at two levels:

- Evaluation of a given model of energy demand against an idealized standard of comparison.
- Evaluation of a given model against the purported desires and scope of the modellers.

The two levels of evaluation serve different purposes. The evaluation of a model against the purported modelling aims of the model-developers indicates just how well the model-developers were able to specify, quantify, develop, and utilize the analytic system they desired. Such an evaluation is very important to model users familiar with the analytic and policy aims of a given model. However, a more onerous model evaluation - against an idealized standard of comparison - is also very useful. While a given model may be well-suited for the particular analyses intended by the model-developers, crucial policy questions and crucial market and geographical disaggregations may have been ignored in the initial aims of modelers.

The eight criteria for energy demand models to be used in the review are as follows:

- i) Proper identification of major market participants and the level of dis-

aggregation required.

While this review focuses upon residential energy demand, some of the inter-fuel substitution models analyze other user sectors as well; hence it is useful to indicate other user sector disaggregations. Four sectors of final use include commercial, residential, industrial and transportation use. One area of intermediate use is the electric utility sector. Residential use can be disaggregated by type of use (home-heating, water heating, cooling, etc.). Commercial and industrial use can be disaggregated by process and comfort use while industrial users can be disaggregated by SIC or technological characteristics.

In most cases, the greater the disaggregation by user sector and fuel use, the better. However, extreme disaggregation may not be useful for all analytic purposes; as a result the thrust of this criteria will depend upon the analytic aims of the modelers.

ii) Proper identification and incorporation into variables in the model of policy issues and technological considerations for the major market participants.

One of the two principal concerns of this model review is to examine the ability of models to assess the competitiveness of new energy technologies and analyze alternative energy policy proposals for the penetration of those technologies. As a result, a crucial criterion is whether the important policy and technological issues have been properly incorporated into the variables and the structure of the models.

The policy issues in general are most easily dichotomized into long-run and short-run issues. In the short-run, a model of energy demand should deal with conservation techniques and policy variables aimed at affecting the utilization of a given stock of fuel-burning equipment (e.g., thermostat control, highway speed limits, appliance use standards). In the long-run, where new technology penetration is crucial, a demand model should deal with such policy and technical

issues as the explicit characteristics of technologies, efficiency standards (taxes) and the effect of them upon changes in the stock of fuel-burning equipment.

iii) Proper degree of geographical disaggregation.

As with criterion i), greater geographical disaggregation is generally better. However, the actual level of disaggregation is more usefully judged against the analytic aims of the model builder.

iv) Utilization of the appropriate behavioral models and underlying behavioral assumptions.

The second principal concern of this review is the appropriate treatment of the dual components of energy demand; to wit demand for fuels and for fuel-burning equipment. Given the identification of the major market participants and the policy and technical issues to be addressed, a wide array of analytic specifications are available for demand analysis; they include partial adjustment models, choice models, consumer utility models, etc. While each type of model provides a powerful tool for analyzing a particular behavioral phenomenon, each model also imposes certain assumptions upon the behavior being analyzed. Such assumptions require critical scrutiny before a model is estimated and utilized for policy. Furthermore, the available analytic specifications can be complicated; as a result, the details of the technical application of the behavioral models also require close scrutiny.

v) Proper integration of the demand analysis into an overall energy and/or macroeconomic model.

This criteria is applicable only to those single fuel or interfuel substitution demand models that are utilized within larger models of energy systems. For purposes of this review, this criterion will be relevant only to several of the interfuel substitution demand analyses. In those cases, a well-specified energy

demand module must be properly integrated into a well-specified overall model of energy in order to simultaneously assess the static interaction of demand and supply and dynamic changes in demand and supply over time.

vi) Utilization of proper data and statistical/econometric techniques.

A comprehensive and well-specified model may prove useless if improper historical data and/or estimation techniques are used. It is not usually possible (given research budget constraints) to subject a given model to rigorous statistical testing including forecasting; backcasting; estimation for sub-sample of data to test parameter estimate robustness; and examination of alternative variables and specifications. However, such analysis can be very useful in assessing the adequacy of the data and the estimation techniques.

Furthermore, in policy simulation, the inputted exogenous variables must adequately represent the policy scenarios being assessed.

vii) Provision of good documentation for the use of the energy demand modelling.

viii) Provision for relatively easy accessibility and extensibility of the modelling effort.

It is not possible for a given model or group of modelers to incorporate or foresee all possible policy simulations or analytic uses. As a result, it is a very desirable characteristic that it is easy to enter the theoretical and computer-coded structure of a model in order to alter or extend particular elements of that model for specific analyses desired by the potential user.

C) MODELS OF DEMAND FOR INDIVIDUAL FUELS

OVERVIEW

In Section A, the Introduction and Summary, it is stated that the demand models would be reviewed to assess their treatment of the dual components of demand - demand for fuels and demand for fuel-burning capital stock. Furthermore, the models will be assessed regarding their treatment of new technologies. Both assessments focus upon the behavioral structure of the models.

In Section B, criterion iv) indicated that there exist many behavioral models for dealing with energy demand. Several of these behavioral models are discussed here. Before that discussion, it is useful to summarize the consumer demand behavior that the models attempt to approximate. That behavior can be thought of as a three step process that spans both the long-run and the short-run:

- The consumer decides whether to buy a fuel-burning consumer durable, capable of providing a particular consumer service (e.g. cooking, heating, lighting, air conditioning, etc.)
- The consumer decides on the characteristics of the equipment he desires, including efficiency, technical characteristics and fuel type. The consumer also decides on whether the equipment is a new or traditional technology.
- Once the equipment is acquired, the consumer determines the frequency and intensity of use.

The first two decisions, which are sometimes simultaneous, are essentially long-run decisions that effect changes in the size and characteristics of the fuel-burning capital stock. The third decision is short-run, taking the capital stock as given.

This Section will indicate how each of the single fuel models approximates these three consumer behaviors.

The models to be reviewed in this section were introduced in Table 1 of Section A and are repeated in Table 2 along with a brief summary of their characteristics.

Table 2 delineates a number of important characteristics of the reviewed models. The level of analysis is usually residential electricity or electrical appliance demand, although some results for residential/commercial electricity demand and gas demand are also reported. The type of data utilized by the models is usually pooled time-series cross-sectional data for states; however, a number of studies utilize more refined disaggregated data at the county meter read-book level. The dependent variable of the single equation models is usually electricity consumption on a total, per capita, per household or per customer basis. In some cases, demand for the appliance stock and demand for gas and oil are also modeled. In one case [Taylor, Blattenberger, Verleger/DRI (29)] study, the dependent variable is the utilization rate of the appliance stock. The explanatory variables in the models usually include own-price (P_o), substitute prices (P_s), income (Y), population (N), weather/climate variables (W), appliance stock data (A), demographic variables (including housing characteristics, degree of urbanization and characteristics of the consuming residences) (D), and a time trend (t).

Examples of static and dynamic models are included. For dynamic formulations, stock adjustment specifications utilizing a lagged endogenous variable are common in the models reviewed. In some cases, appliance prices are also used. The functional form and estimation techniques are identified in Table 2. The price specification is indicated, since in the face of the declining block rate electricity prices, a number of alternative price specifications can be used with different theoretical and empirical implications.

Since the principal reason for this review is to assess the validity of the behavioral assumptions about energy demand inherent in these models particularly

TABLE 2: OVERVIEW OF DEMAND STUDIES

AUTHOR/ ANALYSIS	LEVEL OF ANALYSIS/ TYPE OF DATA	DEPENDENT VARIABLE	EXPLANATORY VARIABLES ^a										FUNCTIONAL FORM/ ESTIMATION TECHNIQUE			
			P ₀	P ₁	Y	N	W	A	D	t	OTHER					
1) ACTON, MITCHELL AND MOWILL (1976)	RESIDENTIAL ELECTRICITY DEMAND MONTHLY DATA FOR METER READ BOOK AREAS IN LOS ANGELES COUNTY, JULY 1972- JUNE 1974	CONSUMPTION BY HOUSEHOLD	X	X	X	X	X	X	X							LINEAR; TOTAL ENERGY EQUALLING THE PRODUCT OF THE APPLIANCE STOCK AND ITS UTILIZATION RATE. DOES CROSS-SECTIONAL AND TIME- SERIES ANALYSIS SEPARATELY.
2) ANDERSON (1972)	RESIDENTIAL ELECTRICITY DEMAND 30 STATES, 1969 CALIFORNIA, ANNUALLY 1947-1969	ANNUAL CONSUMPTION PER FLEXIBLE (NEW) CUSTOMER IN KWH/CUSTOMER YEAR	X	X	X			X					X			LOG-LINEAR, OLS
3) ANDERSON (1973)	RESIDENTIAL APPLIANCE, ELECTRICITY, GAS DEMAND 30 STATES, 1960-1970	oSHARES OF APPLIANCE STOCK BY ENERGY TYPE FOR VARIOUS USES oDEMAND FOR ELECTRICITY/ HOUSEHOLD oDEMAND FOR GAS	X	X	X			X			X					LOG-LINEAR, OLS AND GLS. STATIC AND DYNAMIC FORMULATIONS
4) BALESTRA (1967)	RESIDENTIAL/COMMERCIAL GAS DEMAND 49 STATES AND WASHINGTON, D.C. 1950-1962	GAS IN BTU X 10 ¹² ; INCREMENTAL DEMAND AND TOTAL DEMAND	X		X	X	X				X		LAGGED DEPENDENT VARIABLE			LINEAR, LOG-LINEAR, FIRST DIFFERENCES, 2 SLS, MAXIMUM LIKELIHOOD, PARTIAL ADJUSTMENT FORMULATIONS
5) CARGILL AND MEYER (1971)	ELECTRICITY DEMAND FOR ALL SECTORS 2 SMSA'S, MONTHLY DATA, JANUARY 1965 - DECEMBER 1968	SYSTEM LOAD AT t = 1, 1 = 1, ..., 24. DESEASONALIZED	X	X	X							X	EMPLOYMENT OF PRODUCTION WORKERS IN MANUFACTURING, Y ²			24 HOURLY EQUATIONS; OLS
6) FISHER AND KATSEN (1962)	RESIDENTIAL ELECTRICITY AND APPLIANCE DEMAND 47 STATES 1946 - 1957	DEMAND FOR ELEC- TRICITY IN THE SHORT RUN (KWH) GIVEN FIXED APPLIANCE STOCK DEMAND FOR APPLIANCES IN THE LONG RUN	X		X				X	X			NUMBER OF WIRED HOUSEHOLDS, NUM- BER OF MARRIAGES, KWH CONSUMED PER AVERAGE USE, APPLIANCE PRICES, PERMANENT INCOME.			MULTIPLE REGRESSION AND COVARIANCE ANALYSIS (OF GROUPS OF STATES). OLS ON FIRST DIFFERENCES OF THE LOGARITHMS.
7) GRIFFIN (1974)	RESIDENTIAL ELECTRICITY DEMAND UNITED STATES' AGGREGATE ANNUAL DATA, 1949 AND 1951 - 1971	DEMAND PER CAPITA	X		X				X							25 EQUATIONS, BLOCK RECURSIVE. ALMON LAG. OLS AND 2SLS. "LINKED" TO MACRO MODEL.
8) HALVORSEN (1973)	RESIDENTIAL ELECTRICITY DEMAND 48 CONTIGUOUS STATES, ANNUAL, 1961-69. POOLED TIME SERIES AND CROSS SECTIONAL DATA	AVERAGE CONSUMP- TION OF ELECTRIC ENERGY/CUSTOMER	X	X	X			X	X	X	X		DEGREE OF URBAN- IZATION, APPLIANCE PRICES.			STATIC EQUILIBRIUM MODEL. LOG- LINEAR, 2SLS, IV FOR STATIC EQUA- TION USING DATA 1961 - 1969.
9) MOUTHAKKER (1951)	RESIDENTIAL ELECTRICITY DEMAND 42 PROVINCIAL TOWNS, ENGLAND, ANNUAL DATA, 1937-38	AVERAGE ANNUAL CONSUMPTION OF ELECTRICITY FOR CUSTOMERS ON TWO PART TARIFF.	X	X	X			X	X							LOG-LINEAR.

^a P₀ = GAS PRICE, P₁ = PRICE OF SUBSTITUTE FUELS, Y = INCOME, N = POPULATION, W = WEATHER/TEMPERATURE, A = STOCK OF APPLIANCES.
B = DEMOGRAPHIC/HOUSING CHARACTERISTICS, t = TREND.

^b Y₁ IS TYPICAL ELECTRIC BILL (JPC) AND Y₂ IS TYPICAL GAS BILL (FROM ELS)

TABLE 2: (cont.)

PRICE SPECIFICATION ^{b)}	ELASTICITIES				INCOME	OTHER	STOCK TREATMENT	ADDITIONAL REMARKS
	OWN-PRICE		CROSS-PRICE					
	L.R.	S.R.	L.R.	S.R.				
1) DEALS EXPLICITLY WITH DECLINING BLOCK RATE SCHEDULE, ESTIMATING MARGINAL RATE AND FIXED CHARGE	-.70	-.35		.71	.38 (SR)		DEVELOPS APPLIANCE STOCK ESTIMATE BASED ON AVERAGE MONTHLY CONSUMPTION; AIR CONDITIONERS AND HEATING WEIGHTED BY COOLING AND HEATING DEGREE DAYS	ELASTICITY ESTIMATES FROM POOLED DATA. CROSS-SECTIONAL ELASTICITY ESTIMATES FOR DIFFERENT MONTHS SHOW WIDELY TIME-VARYING RESULTS.
2) TEB (1000 KWH/MO) TEB (500 KWH/MO) AVERAGE REVENUE	-.91			.13	1.13	-.85 SIZE OF HOUSEHOLD .18 WINTER TEMPERATURE .83 SUMMER TEMPERATURE		SEPARATE ROWS OF RESULTS FOR ANALYSIS OF 50 STATES AND CALIFORNIA
	-.88			.17	.34-.46			
3) TFB (1000 KWH/MO) TCB (30 THERMS/MO)	-1.12			.30 GAS	.80	-.94 SIZE OF HOUSEHOLD .76 SINGLE FAMILY UNITS .27 OIL .12 COAL	IN SHARE EQUATIONS	SEPARATE ROWS OF RESULTS FOR THE THREE DEPENDENT VARIABLES
	-2.75			NEGATIVE BUT INSIGNIFICANT FOR OIL, ELECTRICITY AND COAL				
4) AVERAGE PRICE	ELASTICITIES VARY CONSIDERABLY BY STATE AND GROUPS OF STATES POOLED BY HOMOGENEITY IN WEATHER, GAS AVAILABILITY AND TIME PERIOD							INCREMENTAL DEMAND ELASTICITIES SIGNIFICANTLY GREATER THAN TOTAL DEMAND ELASTICITIES. SUBSTITUTES ARE OIL AND COAL.
	-.68	-.03						
5) AVERAGE REVENUE AGGREGATED OVER ALL CLASSES OF CUSTOMERS		-.06 TO -.58			INSIGNIFICANT			DEALS EXPLICITLY WITH TIME OF DAY PRICING. EXPECTS MORE PRICE RESPONSIVENESS IF TIME OF DAY PRICING EXISTED. SIGNIFICANT PRICE CHANGES SHOULD LEAD TO DECREASED CONSUMPTION.
6) AVERAGE REVENUE		INCL. -.16 TO -.25		INCL.	.07 TO .33	APPLIANCE PRICES HAVE NO EFFECT. CHANGES IN NUMBER OF WIRED HOUSEHOLDS AND NUMBER OF MARRIAGES HAVE SIGNIFICANT POSITIVE EFFECT	DISTINGUISHES SHORT RUN DEMAND AS A FUNCTION OF INTENSITY OF USE OF PRESENT STOCK VS. LONG RUN DEMAND AS A FUNCTION OF THOSE VARIABLES WHICH INFLUENCE RATE OF GROWTH OF STOCK OF APPLIANCES.	SUBSTANTIAL DIFFERENCE BETWEEN REGIONS OF THE COUNTRY. AS REGIONS "MATURE" ECONOMICALLY, PRICE SENSITIVITY DECREASES. EMPHASIZES THAT RELATIVE AND NOT ABSOLUTE CHANGES ARE OF IMPORTANCE; HENCE, MOST VARIABLES EXPRESSED IN TERMS OF RELATIVE CHANGE.
		INCL.		INCL.	CURRENT AND PERMANENT INCOME IMPORTANT			
7) AVERAGE REVENUE	-.52	-.06			.06 (SR) .88 (LR)	.22 (CAPITAL STOCK)	AIR CONDITIONERS EXPLICITLY INCLUDED	ONLY RESIDENTIAL ELECTRICITIES REPORTED HERE. MODEL INTENDED FOR SIMULATION. FORECASTS TO 1961. STUDY ALSO DISCUSSES LARGE USERS.
8) HAS SEPARATE PRICE EQUATION FOR MARGINAL PRICE, BUT USES TEB AND AVERAGE PRICE FOR DEMAND	-1.0 TO -1.21			.049 TO .088	.47 TO .54			DEALS EXPLICITLY WITH SIMULTANEITY PROBLEMS. FOR THE PRICE LOCATION SPECIFIED, THE USE OF MARGINAL OR AVERAGE PRICE WILL YIELD THE SAME ELASTICITIES.
9) MARGINAL PRICES (FROM TWO-PART TARIFF), LAGGED TWO PERIODS.		-.9 TO -1.04		+.2 TO +.28	1.01 - 1.17		"HEAVY" EQUIPMENT ONLY AS MEASURED IN TERMS OF KWH RATING.	TENTATIVE INVESTIGATION ON SEASONALITY (HOURS OF DAYLIGHT, AVERAGE TEMPERATURE).

a) P_0 = OWN PRICE, P_s = PRICE OF SUBSTITUTE FUELS, Y = INCOME, N = POPULATION, W = WEATHER/TEMPERATURE, A = STOCK OF APPLIANCES
 b) DEMOGRAPHIC/HOUSING CHARACTERISTICS, t = TREND.

b) TEB IS TYPICAL ELECTRIC BILL (7PC) AND TCB IS TYPICAL GAS BILL (FROM BLS)

TABLE 2: (cont.)

AUTHOR/ ANALYSIS	LEVEL OF ANALYSIS/ TYPE OF DATA	DEPENDENT VARIABLE	EXPLANATORY VARIABLES ^a										FUNCTIONAL FORM/ ESTIMATION TECHNIQUE		
			P ₀	P _s	Y	N	W	A	D	c	OTHER				
10) MONTMARNER, VERLEGER, SHEENAN (1974)	RESIDENTIAL ELECTRICITY DEMAND 48 STATES, 1961 - 1971	KWH CONSUMPTION PER CAPITA	X		X									LAGGED DEPENDENT VARIABLE	1.) LOG-LINEAR, PARTIAL ADJUSTMENT MODEL, GLS, ERROR COMPONENT TECHNIQUE. 2.) OLS WITH AND WITHOUT SAME INTERCEPTS 3.) IV (LAGGED Y, LAGGED P, POPULATION)
11) MOUNT, CHAPMAN AND TYRELL (1973)	RESIDENTIAL COMMERCIAL INDUSTRIAL ELECTRICITY DEMAND, 48 CONTIGUOUS STATES ANNUAL, 1946 - 1970	TOTAL ELECTRICITY DEMAND, KWH x 10 ⁶	X	X	X	X	X							LAGGED DEPENDENT VARIABLE, APPLIANCE PRICES	LOG-LINEAR SPECIFICATION, CONSTANT ELASTICITY MODEL - OLS, VARIABLE ELASTICITY, MODEL - OLS AND IV, USES ERROR COMPONENTS MODEL.
12) MOUNT AND CHAPMAN (1974)	RESIDENTIAL ELECTRICITY DEMAND U.S. CONTIGUOUS STATES, ANNUAL, 1963 - 1972	TOTAL ELECTRICITY DEMAND IN KWH	X	X	X									NUMBER OF CUSTOMERS, APPLIANCE PRICES.	GEOMETRIC LAG, GLS, RANDOM CROSS-SECTIONAL EFFECTS, LOG-LINEAR
13) TAYLOR, BLATTENBERGER, VERLEGER/DRI (1977)	RESIDENTIAL ELECTRICITY, GAS, OIL DEMAND 30 STATES AND WASHINGTON, D.C. 1955 - 1974	RESIDENTIAL CON- SUMPTION OF GAS, ELECTRICITY AND OIL BY STATE APPLIANCE STOCK UTILIZATION RATES CAPITAL STOCK	X	X	X		X		X					LAGGED ENDOGENOUS VARIABLE LAGGED ENDOGENOUS VARIABLE LAGGED ENDOGENOUS VARIABLE, APPLIANCE PRICES	LOG-LINEAR AND LINEAR TRADITIONAL FLOW ADJUSTMENT MODEL; LOG-LINEAR AND LINEAR KOYCK MODEL LOG-LINEAR AND LINEAR FLOW ADJUSTMENT AND KOYCK MODEL LOG-LINEAR OLS, ERROR COMPONENTS MODEL USED THROUGHOUT.
14) WELLS (1977)	RESIDENTIAL ELECTRICITY DEMAND; CONSUMPTION DATA FOR 39 MASSACHUSETTS ELECTRIC UTILITY DIS- TRICTS AND 57 RESIDEN- TIAL RATE STRUCTURES, 1975	MONTHLY CONSUMP- TION IN KWH	X	X	X				X	X				APPLIANCE SATURATION RATES USED	OLS, LOG-LINEAR
15) WILSON (1971)	RESIDENTIAL ELECTRICITY DEMAND 77 CITIES IN 1966	KWH PER HOUSEHOLD AND APPLIANCE DEMAND	X	X	X	X	X	X					X		LINEAR, LOG-LINEAR OLS

^a) P₀ = OWN PRICE, P_s = PRICE OF SUBSTITUTE FUELS, Y = INCOME, N = POPULATION, W = WEATHER/TEMPERATURE, A = STOCK OF APPLIANCES
D = DEMOGRAPHIC/HOUSING CHARACTERISTICS, c = TREND.

^b) TEB IS TYPICAL ELECTRIC BILL (FPC) AND TGB IS TYPICAL GAS BILL (FROM BLS)

TABLE 2: (cont.)

	PRICE SPECIFICATION b)	ELASTICITIES				INCOME	OTHER	STOCK TREATMENT	ADDITIONAL REMARKS
		OWN-PRICE		CROSS-PRICE					
		L.R.	S.R.	L.R.	S.R.				
10)	DIFFERENCES BETWEEN TES FOR 1) 500 & 100 KWH; 2) 250 & 100 KWH, 3) 500 & 250 KWH AS ESTIMATES OF MARGINAL PRICE	-1.0 -1.2 -.45	-.089 -.094 -.029			S.R. = .143 L.R. = -1.6 S.R. = .127 L.R. = -1.6 S.R. = .145 L.R. = -2.2			FORECASTS AND BACKCASTS SURPRISINGLY GOOD FOR SO SIMPLE A MODEL. LITTLE HOMOGENEITY AMONG STATES. FLOW ADJUSTMENT MODEL THE MOST USEFUL SPECIFICATION. ELASTICITIES ARE W.R.T. THE DIFFERENT PRICE DEFINITIONS.
11)	AVERAGE PRICE	-1.2 -1.6 -1.8	-.14 TO -.36	.2 .05 .06	.02	.21 (L.R.) .02 TO .10 (S.R.) .88 (L.R.) .65 (L.R.)	UNITARY (L.R.) W.R.T. POPULATION. INEL. W.R.T. PRICE OF APPLIANCE (L.R.)		THE ABSOLUTE VALUE OF THE PRICE ELASTICITY POSITIVELY CORRELATED WITH PRICE. ELASTICITIES REFER TO RESIDENTIAL, COMMERCIAL AND INDUSTRIAL. IV AND OLS GIVE SIMILAR L.R. ELASTICITIES BUT DIFFERENT S.R. ELASTICITIES.
12)	1.) MARGINAL 2.) AVERAGE 3.) AVERAGE/MARGINAL	-1.7	-.31	.03 TO .61	.01 TO .16	S.R. = -.16 L.R. = -.61			DISCUSSES: EFFECT OF INCREASES IN P ₀ ON GENERATING CAPACITY AND ON PRIMARY FUEL REQUIREMENTS. ALSO EQUATIONS FOR COMMERCIAL AND INDUSTRIAL SECTORS.
13)	MARGINAL AND FIXED CHARGE ELECTRICITY RATES; AVERAGE GAS PRICE	-.82 -1.12 TO -1.0	-.08 -.06 TO -.54 -.02 TO -.22		.02 TO .10	.10 S.R. 1.08 L.R. .0004 TO .38 (S.R.) VARIES WIDELY TO BY APPLIANCE ALL INELASTIC HOWEVER	ELECTRICITY FIXED CHARGE -.02 (S.R.) -.17 (L.R.) -.08 (L.R.) ELECTRICITY FIXED CHARGE	APPLIANCE STOCK VARIABLE A WEIGHTED STOCK USING "NORMAL" USE AS WEIGHTS	REPORTED ELASTICITIES FOR FUEL DEMAND ARE THOSE FOR ELECTRICITY. *VARYING ELASTICITIES FOR REFRIGERATORS, FREEZERS, ROOM AIR CONDITIONERS, WATER HEATERS, STOVES, AUTOMATIC WASHERS, DRYERS, CENTRAL HEAT AND CENTRAL AIR CONDITIONERS.
14)	MARGINAL AND FIXED CHARGE ELECTRICITY RATES; AVERAGE GAS PRICE		-.08			.32 (S.R.)		HANDLES APPLIANCE STOCK THRU SATURATION RATES IN EQUATIONS	
15)	TES FOR 500 KWH/MO	-1.33		0.31		-0.46		APPLIANCE STOCK IS A FUNCTION OF "LIFE STYLE." SEPARATE EQUATION, DEPENDENT VARIABLE: X HOUSES WITH AT LEAST 1 UNIT OF APPLIANCE I. (I = 1....6) 6 DIFFERENT CATEGORIES.	PRICE IS THE MAJOR DETERMINANT.

a) P₀ = OWN PRICE, P₁ = PRICE OF SUBSTITUTE FUELS, Y = INCOME, N = POPULATION, W = WEATHER/TEMPERATURE, A = STOCK OF APPLIANCES
B = DEMOGRAPHIC/HOUSING CHARACTERISTICS, t = TREND.

b) TES IS TYPICAL ELECTRIC BILL (FPC) AND TGS IS TYPICAL GAS BILL (FROM BLS).

with respect to new technologies, estimates of behavioral sensitivity are crucial products of the models. Various elasticity estimates for each model are therefore reported, principally own-price, cross-price, and income elasticities in the short and long run. Other selected elasticities are indicated. Such elasticity estimates are determined by the interaction of four elements: type of data used in the model, the specification of the dependent and independent variables, the equation formulation, and the estimation techniques. A comparison of the elasticities of the models in Table 2 will help in evaluating the effects of the interaction of specific forms of these four elements in each model. Table 2 also indicates how appliance stocks are treated.

This overview and the facts detailed in Table 2 assume a knowledge on the part of the reader of the meaning of such technical terms as static model, dynamic model, partial adjustment formulation, and elasticity. Furthermore a basic understanding of econometric modelling issues is assumed.

The discussion of this section proceeds by model/analysis documented in Table 2. Once each model is documented, the summary will critically overview the models.

1) ACTON, MITCHELL AND MOWILL (1976) (AMM) MODEL

The authors examine (1) demand for electricity based on highly disaggregated monthly data from Los Angeles County over the period 1972 to 1974. Their theoretical formulation explicitly differentiates the long-run and short-run; for the short-run analysis, they treat appliance stock as fixed and concentrate on modelling the factors that determine capital utilization. They utilize theoretically appropriate variables including disaggregated appliance stock data, marginal and fixed-charge electricity prices and weather. Possibilities of errors in variables and aggregation biases are lessened by the level of data disaggregation utilized by the study.

The AMM model treats consumer behavior as the three step process outlined in the Overview of this Section. Those were:

- The consumer decides whether to buy a fuel-burning consumer durable, capable of providing a particular consumer service.
- The consumer decides on the characteristics of the equipment he desires, including efficiency, technical characteristics and fuel type.
- Once the equipment is acquired, the consumer determines the frequency and intensity of use.

The first two decisions are treated correctly by the authors as long-run. AMM then focus upon the determinants of the third decision, the short-run capacity utilization decision. By explicitly dichotomizing the short-run and long-run in this fashion, AMM permit a theoretically sound analysis with a richer specification in terms of policy variables and socioeconomic and technological characteristics.

The short-run fuel demand is specified as

$$E_t = U(P_{et}, P_{st}, Y_t, Z_t, A_{st}) * A_{et} \quad 1a)$$

while long-run appliance demand is specified as

$$A_{et} = F(P_{et}, P_{st}, Y_t, Z'_t) \quad 1b)$$

where E_t is the consumption of electricity in month t

A_{et} is the stock of electricity consuming appliances in t

A_{st} is the stock of other fuel consuming appliances in t

P_{et} is the price of electricity (measured by multi-part tariff)

P_{st} is the price of substitutes (AMM look at gas only)

Y_t is income

Z_t includes all other exogenous factors affecting short-run appliance util-

ization, including weather, household characteristics, etc.

Z'_τ includes all other exogenous factors affecting long-run appliance demand

τ reflects periods earlier than t , hence the long-run.

AMM examine the present theory of nonlinear declining multi-part tariff schedules and develop a marginal rate and an associated fixed charge. For gas only average prices are used. AMM specify 1a) as

$$E_t = a_0 + U_1(X_t) + U_2(X_t) A_{et} + \epsilon_t \quad 2a)$$

allowing different responses in intensity of utilization with respect to measured appliances ($U_2 * A_e$) and uses of electricity such as lighting for which no adequate stock measure is available (U_1). Using a linear specification AMM obtain

$$E_t = a_0 + \sum_i a_i X_{it} + \sum_i b_i X_{it} A_{et} + \epsilon_t \quad 2b)$$

where X_t includes all exogenous variables in 1a). Measuring the appliance stock A_{et} as a composite average of eight major electrical appliances¹ weighted by average monthly consumption of those appliances, AMM obtain

$$A_{et} = \gamma_1 (\%AC) \frac{CDD_t}{\overline{CDD}} + \gamma_2 (\%AH) \frac{HDD_t}{\overline{HDD}} + \sum_{i=3}^8 \gamma_i A_i \quad 3)$$

where A_i = percentage of households with i^{th} electric appliance,

γ_i = mean consumption of i^{th} appliance in kwh/month,

(%AC) = percentage of houses with air conditioning, weighted further by monthly cooling degree days (CDD_t / \overline{CDD}),

(%AH) = percentage of houses with electric heating, weighted further by monthly heating degree days (HDD_t / \overline{HDD}).

Substituting 3) into 2b) yields the equation that AMM estimate using monthly data for the cross section of meter read-book areas in Los Angeles County. The exogen-

¹The eight electric appliances are air conditioners, space heaters, stoves, clothes dryers, water heaters, dishwashers, refrigerators, and television sets.

ous variables that AMM include in X_t are the marginal prices of electricity and gas, the fixed customer electricity charge, average income per household, average number of rooms per household, average monthly rent per household, average market value of the owner occupied housing, percentage of homes in a given observation that are rented, and average number of persons per housing unit.

The interested reader should refer to the full analysis for all elasticity estimates. The more important ones are summarized in Table 2. While the own-price elasticities vary from $-.06$ to -1.03 for different seasons, the average short-run monthly elasticity is $-.35$ (relatively inelastic). The effect of the fixed customer charge was nearly zero and seldom significant. The elasticity with respect to income is $.38$ and the cross elasticity is a relatively high $.71$.

2,3) ANDERSON MODELS (1972, 1973) ¹

Anderson (4,5) examines residential electricity demand in terms of annual consumption for "flexible" (i.e. new) customers in his 1972 and 1973 analyses. In the 1973 analysis he also models demand for appliance stocks. In the 1972 analysis Anderson uses OLS on both the 1969 cross-sectional data and the 1947-1969 California data. In the 50 state case, the demand for electricity is hypothesized to be a function of gas and electricity prices (typical electric bills), average household income, average number of persons per household, fraction of population living in non-metropolitan areas, average January and July temperatures and the percentage of all electric customers. For the California data, only gas and electricity prices, average per capita income, and time were used. The 50 state regression results indicate electricity demand is significantly affected by all variables except gas costs and average January temperature.

The 1973 analysis utilizes both static and dynamic specifications for the 50 states using 1960 and 1970 data. Since the dynamic and static results differ

¹Since much of the material in both Anderson pieces is similar, further references to Anderson include both the 1972 and 1973 analyses, unless only one article is being referenced.

little, Anderson only reports the static results. His energy demand equations for gas and electricity are functions of own and substitute prices (coal, utility gas, bottled gas, fuel oil, electricity, and kerosene), appliance prices, household income, household size, urbanity (i.e. fraction of total house that are nonurban), housing characteristics (percent of total that is single family), winter and summer temperatures (mean December and July temperatures).

Anderson's analysis deals with the differences between short-run and long-run demand differently than AMM. He differentiates between energy customers that choose to stay locked into a particular pattern of energy using appliances and those that choose to make major changes in their stock of appliances. Anderson furthermore assumes that because of force of habit and low variable-to-fixed cost ratio for most electricity using devices, short-run demand by locked in customers is "nearly if not totally unresponsive to changes in income and gas and electricity costs." Thus, short-run elasticities $\equiv 0$, which is a rather severe assumption in light of the analyses suggesting significant, if small, short-run sensitivity.

Anderson assumes that total demand in any year D_t is therefore the sum of locked-in demand from the previous year, δD_{t-1} (where δ is the fraction of locked-in customers) plus flexible demand (the number of new customers times the average demand per flexible customer). In short,

$$D_t = \delta D_{t-1} + F(X) * (H_t - \delta H_{t-1}) \quad 4a)$$

where D_t is total demand in year t

δ is the proportion of lock-in customers

H_t is the number of residential customers

$H_t - \delta H_{t-1}$ is the number of incremental customers, new plus non locked-in and $F(X)$ is average demand per flexible customer, a function of exogenous variables. By manipulation Anderson makes average electricity consumption per flexible (incremental) residential customer a function F of X :

$$\frac{D_t - \delta D_{t-1}}{H_t - \delta H_{t-1}} = F(X); \quad 4b)$$

given estimates¹ of δ , D_t , H_t , and X , the parameters of F can be estimated given specifications for F . Anderson tries in his 1972 analysis linear, log-linear, exponential, and combinations of log-linear and exponential specifications.

In the 1973 analysis, Anderson utilizes equation 4b) for analyzing total energy demand. He also develops appliance demand equations that focus upon inter-fuel substitution. The interfuel substitution modelling and results are listed in Table 2; however, this work will be discussed in Section C when models of inter-fuel substitution are assessed.

The price specifications in the two Anderson analyses of energy demand are similar-typical electric bills. The long-run own-price elasticities for the three separate data sets are similar, between $-.88$ and -1.12 . In the 1972 analysis, the gas cross elasticities are $.13$ to $.17$, indicating much lower cross price sensitivity than the AMM results. In the 1972 and 1973 cross-sectional results, the long-run income elasticities are between $.80$ and 1.13 . However, for the time series data in the 1972 analysis, the income elasticity is between $.34$ and $.46$. The time series analysis excludes a number of variables which could be biasing the income elasticity toward zero. However, the cross-sectional analyses may be attributing state locational effects to income and may be biasing the income elasticity away from zero.

It is interesting to note for the pooled time-series/cross-sectional analysis of AMM where variable specification and data is quite refined and disaggregated, that the short-run income elasticity is $.38$, suggesting a long-run elasticity closer to the Anderson cross-sectional estimates rather than his time-series estimates.

¹When Anderson attempted to estimate δ , given D, H , and X , the estimate was zero. Such a value is impossible. As a result he estimates equation 4b) using varying values of δ . See Anderson (5).

Anderson utilizes the same equational specification for gas demand finding a much greater long-run own elasticity (-2.75) and cross elasticities not significantly different from zero. The higher own elasticity may reflect locational effects biasing the estimate away from zero; for states where gas is less easily available, the gas is more costly on an average price basis due to larger transmission costs and pipeline costs spread over smaller quantities.

4) THE BALESTRA (1967) MODEL

Balestra (7) formulates a wide variety of static and dynamic models. His short-run static equations include gas demand as a function of price and income:

$$G_t = f_1(P_t, Y_t); \quad 4c)$$

gas demand as a function of appliance stock S_t and utilization rates λ_ϵ :

$$G_t = AP_t^\alpha Y_t^\beta S_t \quad 4d)$$

gas demand as a function of price (P_t) and total fuel demand (F_t):

$$G_t = F_2(P_t, F_t) \quad 4e)$$

where total fuel demand F_t can be a function of income Y_t and population N_t . The dynamic formulations utilize these same specifications but also introduce a partial adjustment specification which makes current gas demand a function of lagged demand in the Koyck-Nerlove form. Balestra develops a number of formulations involving lagged and first differenced values for own-price (P_o), substitute prices (P_s), income (Y), population (N), percentage of state population that is urban (U), and weather conditions. While Balestra estimates a wide variety of specifications, one of his basic estimating equations is

$$G_{ti} = \alpha_0 + \alpha_1 P_{g_{ti}} + \alpha_2 P_{s_{ti}} + \alpha_3 N_{t-i,i} + \alpha_4 \Delta N_{ti} + \alpha_5 Y_{t-1,i} + \alpha_6 \Delta Y_{ti} + \alpha_7 U_{ti} + \alpha_8 G_{t-i,i} \quad 4f)$$

where t is the time period and i indexes states.

The elasticity estimates vary considerably by state and for the groups of

states pooled by homogeneity in terms of weather, gas availability, and time period. Gas demand is found to be extremely inelastic in the short-run, $-.03$, and fairly inelastic in the long-run, $-.68$. These estimates differ considerably from the high own-price gas elasticities found by Anderson. The extremely low short-run elasticity is, however similar to Anderson's assumed zero elasticities for locked in demand.

5) CARGILL AND MEYER (1971), (CM) MODEL

The Cargill and Meyer (20) model focuses upon total demand for the residential, commercial and industrial sectors; however the analysis is one of the few that focuses upon time of day demand. As a result it is included in this review. They do load modelling using data for monthly observations on the 24 hour load curve in one hour intervals for two SMSA's (one industrial Midwest city and one West coast city) over January 1965 through December 1968. The CM demand function estimates system load per capita in hour i

$$q_i = \beta_{1i} + \beta_{2i} \frac{P_e}{P_g} + \beta_{3i} Y + \beta_{4i} Y^2 + \beta_{5i} M + \beta_{6i} t + U_i \quad 5)$$

where

$\frac{P_e}{P_g}$ is the price of electricity relative to the price of gas (average revenue per kwh/average price per therm)

Y is real per capita personal income

M is employment of production workers in manufacturing

t is time (1,2...48) in months

β_{ji} are estimated for each time period i

The equation is estimated for each of 24 hours; the variables explain about 90% of the variation in monthly hourly demand. The income effect is of little consequence. The price elasticities vary from $-.06$ to $-.58$. In both cities the demand is less elastic in the afternoon and late morning and more elastic in the evening and early morning before dawn, suggesting more discretionary uses at that time. The fact that

system load includes residential, commercial and industrial demand makes it difficult to interpret the elasticities results with respect to any one of the using groups. Thus the modelling results are not immediately relevant to the purposes of respecifying residential demand models. However, the insights gained from modelling hourly demand are useful.

6) FISHER AND KAYSEN (1962), (FK) MODEL

The FK (36) modelling effort is one of the earliest; however, it contains one of the better treatments of the differences between the short-run and long-run. It is surprising that the insights found in this effort did not show themselves more fully in later work. Not until the AMM work (1) and the analyses by Taylor, Blattenberger, Verleger/DRI (29) did the explicit separate treatment of the long-run and short-run resurface in the literature.

In the short-run, FK accept the appliance stock as fixed and focus upon the determinants of the appliance utilization rate. They define total short-run demand (D_t) as

$$D_t = \sum_{i=1}^n K_{it} W_{it} \quad 6a)$$

where W_{it} is the average stock of appliance i measured in kwhs consumed during a "normal" hour of use in year t , and K_{it} is the intensity of use of the i^{th} appliance in year t for n appliance types. FK assume short-run fuel switching is negligible (as opposed to AMM) and make the intensity of use K_{it} a function of user price and income:

$$K_{it} = A_i P_t^{\alpha_i} Y_t^{\beta_i} \quad 6b)$$

Hence

$$D_t = \sum_{i=1}^n A_i P_t^{\alpha_i} Y_t^{\beta_i} W_{it}$$

and substituting $C_i \equiv A_i \bar{P}^{\alpha_i} \bar{Y}^{\beta_i}$

$$D_t = \sum_i^n C_i (P_t/\bar{P})^{\alpha_i} (Y_t/\bar{Y})^{\beta_i} W_{it} \quad 6c)$$

$$= C (P_t/\bar{P})^\alpha (Y_t/\bar{Y})^\beta \sum_i^n W_{it} \quad 6d)$$

if $\alpha_i = \alpha$, $\beta_i = \beta$, $C_i = C$ for all i . Taking logs one obtains the FK basic equation

$$D_t' = A' + \alpha P_t' + \beta Y_t' + W_t' + U_t \quad 6e)$$

where primes denote logarithms, $A = \bar{C} \bar{P}^{-\alpha} \bar{Y}^{-\beta}$ and $W_t = \sum_i^n W_{it}$.

If proper estimates of the weighted appliance stock (W_t) were available, 6e) could be estimated. FK felt the data was not good enough; hence they assumed that W_t grew exponentially in each state over the sample period. As a result, when taking first difference in 6e), $\ln W_t - \ln W_{t-1}$ is constant and subsumed into A' . This assumption seems to be too severe for all states; FK's analysis of the explanatory power of the equation (R^2) related to state's growth rate indicates that for the fastest growing states, the assumption of simple exponential growth in W_t is least supportable.

Estimating 6e) with assumed exponential growth in the appliance stocks for all states over 1946-1957 using average revenue as the price specification yields price elasticities that vary from -.03 to -.99 and income elasticities that vary from .06 to .88 (when they have the correct sign.) In order to explain the differences in these estimates, FK claim that greater urbanization is associated with greater income and price elasticities, reflecting the stock of appliances in urban areas and the more numerous substitutes available. When FK pool states by homogenous regions based upon urbanized or rural characteristics, all elasticity estimates become significant and $e_p = -.16$ to $-.25$ while $e_y = .07$ to $.33$.

While some of FK interpretations as to the reasons why elasticities differ

across urban and rural, old and young states can be debated and seem contradictory¹, on the whole their elasticity estimates for pooled data yield short-run elasticities estimates that corroborate such efforts as AMM; to wit $e_p \approx -.2$ and $e_y \approx .25$.

For long-run demand, FK focus explicitly upon changes in the stock of consumer appliances. FK first examine linear and logarithmic forms of the partial adjustment model. However, they scrap the partial adjustment model because it ideally models variables that exhibit the possibility of continuous variability in the stock to desired levels (e.g. investment in all consumer durables). In this case, the estimate of the partial adjustment parameter ($0 < \lambda < 1$) makes sense. With appliance purchases by new households, the household either buys the new appliance or not; room for continuous variability is lacking. In the face of these difficulties (FK utilized a "disease model" relating W_{it}/W_{it-1} - i.e. "spread-of the disease") to the independent variables² as follows:

$$\begin{aligned}
 W_{it}' - W_{it-1}' &= A_i + \eta_{i1}(Y_t^E - Y_{t-1}^E) + \eta_{i2}Y_t' + \eta_{i3}E_{it}' + \eta_{i4}G_{it}' \\
 &+ \eta_{i5}(H_t' - H_{t-1}') + \eta_{i6}(F_t' - F_{t-1}') + \eta_{i7}M_t' + \eta_{i8}P_t^E \quad 7) \\
 &+ \eta_{i9}\gamma_{it}' + \eta_{i10}V_t^E + U_{it}
 \end{aligned}$$

where primes denote natural logs,

$W_{it}' - W_{it-1}' = \ln(W_{it}/W_{it-1})$ = the log of the change in appliance stocks of type i for years t and $t-1$

Y_t^E = seventeen-year moving-average of real personal income per capita (Friedman's permanent income)

¹See pp. 29-60, where FK claim more urbanized states tend to have higher elasticities while younger states also have greater elasticities.

²For full definition and data sources see FK (36), pp. 85-90.

Y_t = current personal income per capita
 E_{it} = electric appliance price
 G_{it} = gas substitute appliance price
 H_t = number of customers per capita (i.e. customers/population)
 F_t = population
 M_t = moving average of marriages in t and t-1
 P_t^E = user cost of electricity (average revenue)
 γ_{it} = appliance efficiency, kwh consumption of appliance per hour of average use

and V_t^E = three year moving average of gas prices.

FK find that net changes in appliances depend primarily on changes in long-run income, population, the number of wired households per capita, and number of marriages. Except for electric ranges and water heaters, the cost of electricity and the price of the appliance have little effect upon stock demand. For washers and refrigerators, economic variables are unimportant.

The apparent lack of importance of economic variables contradicts much of the interfuel substitution literature. However, the contradiction is spurious. FK find economic variables unimportant for washers and refrigerators where there is little interfuel substitution; for these devices, current and permanent income, population and number of wired households have the greatest explanatory power. For ranges and water heaters greater possibilities for interfuel substitution exist and FK find the economic variables have greater explanatory power. If space heating were analyzed I am sure FK would have found even better explanatory power in the economic (own and cross operating prices and appliance costs) variables.

7) GRIFFIN (1974) MODEL

Griffin (37) develops a 25 equation, block recursive model of electricity supply and demand. For his residential demand specification he hypothesizes per cap-

ita consumption to be a function of capital stock per capita, income and fuel prices. He estimates

$$\frac{\dot{DR}}{N} = \alpha_0 + \alpha_1 \frac{K_1}{N} + \sum_{i=0}^m \beta_i \left(\frac{YD}{N}\right)_{-i} + \sum_{i=0}^n \lambda_i \left(\frac{PR}{P}\right)_{-i} + \epsilon \quad 8)$$

where

- DR is the total residential electricity demand
- N is population
- K_1 is the stock of residential appliances (proxied by central air conditioners)
- YD is real disposable income
- PR is the average residential electricity price
- P is the GNP deflator.

Griffin also estimates per capita appliance stock as a lagged function of real disposable per capita income. However due to data problems, he again models capital stock as central air conditioners alone.

Griffin finds that the short-run own-price electricity is -.06 and the long-run elasticity is -.52. The respective income elasticities are .06 and .88. The stock elasticity is .22 which is very small; it probably reflects the fact that only central air conditioners are included in estimates of the appliance stock.

8) HALVORSEN (1973) MODEL

Few of the analyses summarized in Table 2 deal explicitly with the simultaneity difficulties inherent in modelling electricity demand. Halvorsen (38-42) attempts to do so by specifying both supply and demand curves as follows:

$$\text{Demand: } Q = Q(P_m, Y, Z, U) \quad 9a)$$

$$\text{Supply: } P_m = P(Q, C, v) \quad 9b)$$

where Q , the quantity demanded, is a function of marginal electricity prices (P_m), income (Y), and Z is a vector of other exogenous determinants. The supply/price equation makes marginal electricity prices a function of quantity supplied and costs of supply (C). v and u are disturbance terms. The factors that Halvorsen includes in Z are price of gas, price of electric appliances, percentage of population living in rural areas, number of heating degree days, average size of households, average July temperature, percentage of housing units in multi-unit structures. Halvorsen estimates the structural equations 9a) and 9b) and reduced form equations with various lag structures. He finds that the static model works as well as the dynamic model, and utilizes the static formulation for most of the analysis. However his tests upon the static versus dynamic character of the model are based upon 1961-1970 data when the independent variables were smoothly trending. Similar experiments based upon 1970-1975 experience would more conclusively determine the relative performance of the static and dynamic models' predictive power.

Halvorsen's structural demand equations are credible; however, the supply/price equation is relatively ad hoc and poorly specified. As a result, elasticities estimated from the demand equation appear to be believable; however, total system elasticities based upon 9a) and 9b) are suspect given difficulties in the estimated supply/price relationship. Demand elasticities from the structural demand equation indicate statistically significant long-run own-price elasticities of $-.049$ to $-.088$ and income elasticities of $.47$ to $.54$. These estimates differ for regionally pooled data. In various regions, household size, July temperature and time become significant. The use of marginal and average electricity prices yield very similar elasticity estimates. Halvorsen uses nominal prices, which is a problem.

9) HOUTHAKKER (1951) MODEL

Houthakker's analysis (54) focuses upon a cross-section of 42 provincial towns in the United Kingdom for 1937 and 1938 using the equations

$$X = aM + b/P + cq + dh + \epsilon \quad 10a)$$

and $\ln X = \alpha \ln M + \beta \ln P + \gamma \ln q + \delta \ln h + \epsilon'$ 10b)

where

X is average annual electricity consumption per customer on a 2 part tariff

M is average money income

P is marginal price of 2 part tariff

q is marginal price of gas on domestic tariffs

h is customer holdings of heavy domestic equipment

Gas and electricity prices are lagged 2 years to avoid simultaneity problems.

This specification is similar in spirit to AMM and FK in that appliance stocks are held constant and short-run demand is predicted on the basis of prices and income. The estimated short-run elasticities are: $e_y = 1.17$, $e_p = -.89$, $e_q = .21$, and $e_h = .18$, which are high when compared with other studies. The higher price elasticities may reflect the fact that prices are lagged two years; hence the elasticities are closer to long-run estimates.

10) HOUTHAKKER, VERLEGER, SHEEHAN (1974), (HVS) MODEL

The HVS model (56) differs from the previous models in that it does not explore a wide array of independent variables. It utilizes only electricity price and income in a flow adjustment formulation. Thus, HVS define desired equilibrium consumption Q_{it}^* to be

$$Q_{it}^* = \alpha P_{it}^{\gamma} Y_{it}^{\beta} \quad 11a)$$

while the adjustment mechanism is

$$Q_{it}/Q_{it-1} = (Q_{it}^*/Q_{it-1})^{\theta} \quad 11b)$$

Hence, HVS obtain

$$\ln Q_{it} = \theta \ln \alpha + \theta \gamma \ln P_{it} + \theta \beta \ln Y_{it} + (1-\theta) \ln Q_{i,t-1}$$

HVS utilize a pooled time-series of cross-sections for states from 1961-1971. They

utilize an error components technique which allows for a state component in the error term. The use of the state error component corrects for differences across states that are not included in the price and income effects. HVS use three different price specifications: the differences between typical electric bills (TEB) for 500 and 100 kwh, 250 and 100 kwh and 500 and 250 kwh. The elasticities resulting from these price specifications are listed in Table 2. For the first two prices, low short-run elasticities and long-run elasticities of about -1.2 to -1.6 result. For the third price specification, similar short-run elasticities are estimated; however the long-run price elasticity estimate is much lower. The 500 and 250 kwh difference is the most relevant of the three price variables; hence, the lower long-run elasticity estimate of -.45 must be taken seriously.

In a thorough examination of the HVS model, Charles River Associates (25) found similarly small long-run price elasticities for equations utilizing the 500-250 kwh TEB. However, for the price variable expressed as the difference between TEBs for 1000 and 500 kwh, the long-run price elasticity is estimated to be -1.085 and the long-run $e_y = .63$. These estimates are much closer to the static equilibrium model estimates of Halvorsen and Anderson. In spite of its simplicity, the forecasting and backcasting performance of the HVS model is shown in the CRA work to be quite good, when actual values of the lagged endogenous variable are used.

11) MOUNT, CHAPMAN AND TYRRELL (1973), (MCT) MODEL

MCT (68) model the residential, commercial and industrial sectors individually. They utilize a flow adjustment model with a lagged endogenous variable. Furthermore, in addition to the usual constant elasticity model specification, MCT specify a variable elasticity model. The constant elasticity model (CEM) is:

$$Q_{it} = A Q_{it-1}^\lambda V_{1it}^{\beta_1} \dots V_{Nit}^{\beta_N} \quad 12a)$$

where i is the state
 t is the year

Q is the quantity of electricity demanded

V_n is the level of the nth causal factor

In the partial adjustment formulation, the short-run elasticity (e_{SR}) of Q with respect to V_i is β_i and the long-run elasticity (e_{LR}) is $\beta_i/(1-\lambda)$. The two variable elasticity models are

$$Q_{it} = A Q_{it-1}^\lambda V_{1it}^{\beta_1} \dots V_{Nit}^{\beta_N} e^{\gamma_1/V_{1it}} \dots e^{\gamma_N/V_{Nit}} \quad 12b)$$

and

$$Q_{it} = A e^{\delta_0/D_{it}} Q_{it-1}^\lambda V_{1it}^{\beta_1 + \delta_1/D_{it}} \dots V_{Nit}^{\beta_N + \delta_N/D_{it}} e^{\gamma_1/V_{1it}} \dots e^{\gamma_N/V_{Nit}} \quad 12c)$$

where all the variables are defined above and D is a demographic/geographic shift variable. For 12b) $e_{SR} = (\beta_i - \gamma_i/V_i)$ and $e_{LR} = (\beta_i - \gamma_i/V_i)/(1-\lambda)$. For 12c), $e_{SR} = [\beta_i - (\gamma_i/V_i) + (\delta_i/D)]$ and $e_{LR} = e_{SR}/(1-\lambda)$. These variable specifications permit elasticities to vary with region (i.e. demographic/geographic values for D) and with levels of the independent variables (e.g., if income elasticities vary with $y \equiv V_{kt}$, then $\gamma_k/V_k \neq 0$). MCT utilize OLS and instrumental variables (IV) techniques in estimation. Their price specification is average price. Their independent variables are real personal income per capita, gas price measured as average revenue, price of appliances of machinery, mean January temperature and population. They estimate the equation in log-linear form.

The long-run estimates for both OLS and IV techniques are quite similar; the short-run estimates differ considerably. Since $e_{LR} = e_{SR}/(1-\lambda)$, the reason is that the estimate of the partial adjustment factor is lower in the IV case while the short-run elasticity estimates are higher. The elasticity estimates in Table 2 are OLS results. The long-run own price elasticity is -1.2. This estimate holds for the constant and variable elasticity models, for the OLS and IV estimates.

The long-run gas cross-elasticity is .2, while the income elasticity is .21. The respective own-price, gas cross-price and income short-run elasticities are (-.14 to -.36), .02 and (.02 to .10). Thus the estimated short-run OLS elasticities are extremely small. The IV estimates are more believable because they are statistically consistent. As stated above, the long-run IV estimates are similar to those in Table 2. The short-run IV estimates are about twice as large; hence, they are still inelastic. Overall, in the long-run electricity demand is price elastic and increasingly so as prices rise. Demand is income inelastic and increasingly so as income rises. Demand is unitarily elastic with respect to population.

12) MOUNT AND CHAPMAN (1974), (MC) MODEL

Utilizing a similar modelling approach, MC (68A) examine alternative price specifications for residential electricity demand. The resulting elasticity estimates are quite similar to those found in MCT except for the income elasticity estimates which are somewhat larger.

13) TAYLOR, BLATTENBERGER, VERLEGER/ DRI (1977), (TVB) MODEL

TBV (29) analyze residential energy demand at three levels: demand for gas, oil and electricity by state; demand for appliance services through appliance stock utilization rates; and demand for appliances. TBV deal with the differences between short-run and long-run consumer behavior similarly to Fisher and Kaysen: they distinguish between short-run demand as a choice of the capital stock utilization rate and long-run demand as a choice of the size and characteristics of the appliance stock. As with the Acton, Mitchell and Mowill analysis, TBV deal explicitly with the consumer theory of demand functions in the face of declining block tariff schedules. They utilize as a result both a marginal price and inframarginal fixed charge in fully articulating the budget effects of electricity rates.

For means of comparison TBV introduce the flow adjustment model utilized to explain energy demand similar to that of Houthakker and Taylor (55):

$$\dot{q}_t = \theta(q_t^* - q_t) \quad 13a)$$

with

$$q_t^* = \alpha_0 + \alpha_1 x_t + \alpha_2 \pi_t + \alpha_3 z_t \quad 13b)$$

and therefore

$$\dot{q}_t = \alpha_0 \theta - \theta q_t + \alpha_1 \theta x_t + \alpha_2 \theta \pi_t + \alpha_3 \theta z_t \quad 13c)$$

where q is the amount of electricity (or natural gas or fuel oil) consumed, x is income, π is price (for electricity, consisting of a marginal and a fixed component) and z is a vector of other exogenous factors.

The appliance stock utilization models are of the form

$$q = u(x, \pi, z)S \quad 13d)$$

where the utilization rate of appliance stock S is a function u of x , π , and z as defined above. Whereas the flow adjustment model in 13a) - 13c) do not explicitly deal with the characteristics and size of the appliance stock, the model in 13d) assumes that the appliance stock is given in the short-run. The utilization rate is a function of current variables. Utilization rates for subgroups of appliances can also be examined:

$$q = u^1(x, \pi, z)S^1 + \dots + u^m(x, \pi, z)S^m$$

Equation 13d) can also be expressed and estimated as

$$q/S = u(x, \pi, z) \quad 13e)$$

Equation 13d) requires aggregation of appliance stocks. Fisher and Kaysen utilized "normal use" as weights. TBV do the same so that

$$S_t = \sum_{i=1}^n w_i S_{it}$$

where S_{it} is the stock of the i th type of appliance and w_i is the weight where

$$w_i = \frac{u_i^*}{\sum_j u_j^*}$$

and u_i^* denotes the "normal" utilization rate of the i th appliance.¹

To complement the stock utilization models, a model of capital stock accumulation is required. TBV define equilibrium appliance stocks S^* to be

$$S^* = \beta_0 + \beta_1 x + \beta_2 \pi + \beta_3 (r + \delta)P + \beta_4 z \quad 13f)$$

where x , π and z are defined above and r is the market rate of interest, δ is the depreciation rate of the appliance stock and P denotes the per watt price of additions to the appliance stock. Hence, $(r + \delta)P$ is a user cost of capital services per watt. Combining 13f) with an assumption about replacement investment and the partial adjustment formulation that new investment = $\phi(S^* - S)$, TBV obtain¹

$$y = \phi\beta_0 + \phi\beta_1 x + \phi\beta_2 \pi + \phi\beta_3 (r + \delta)P + \phi\beta_4 z + (\delta - \phi)S \quad 13g)$$

where y is gross investment in appliances.

Equations 13d) and 13g) are the explicit short-run/long-run dichotomization of the simultaneous consumer decisions that are subsumed into the usual partial adjustment or flow adjustment models.² The partial adjustment and flow adjustment models yield similar elasticity estimates in the log-linear specification; the first row of TBV elasticity estimates in Table 2 are those from the flow adjustment model utilizing in addition to x and π , the price of natural gas, heating degree days, and cooling days in z . The resulting own-price elasticities are $-.82$ and $-.08$ in the long-run and short-run. The elasticities with respect to the fixed electricity charge are $-.17$ and $-.02$ in the long-run and short-run. The income elasticities are $.10$ and 1.08 in short-run and long-run.

The second and third rows of elasticity estimates in the TBV analysis results refer to the capital stock equations 13e) [or 13d)]and 13f). x , π and z are defined

¹See Taylor, Blattenberger, Verleger/DRI (29) for details.

²To be precise, the flow adjustment and partial adjustment models differ slightly in their specification. They are compared fully by TBV(29) chapter 5.

as above.

The short-run own-price elasticities vary from -.06 to -.54 depending upon the specification of 13e). Since not all the equations were estimated in a dynamic form, it is difficult to ascribe long-run elasticities for each of these short-run estimates. A reasonable bound is -.12 to -1.0. The cross-price elasticity estimate is nearly zero; hence there seems to be little interfuel substitution in the short-run, a fact assumed by Fisher and Kaysen and found by Anderson. The capital stock equation 13f) is estimated for refrigerators, freezers, room air conditioners, water heaters, stoves, automatic washers, conventional washers, dryers, central heating and central air conditioners. The own-price (marginal price) elasticity estimates vary from -.02 to -.22. The cross-price elasticity estimates vary from .02 to .10. Income elasticity and user capital charge elasticity estimates vary widely for the different appliances analyzed.

Long-run elasticities of energy use can be estimated by assessing the total effect of changes in the independent variables upon appliance stocks and utilization rates:

$$\frac{\partial q}{\partial z} \frac{z}{q} = \frac{\partial(q/s)}{\partial z} \cdot \frac{z}{(q/s)} + \sum_i w_i \frac{\partial S_i^*}{\partial z} \frac{z}{S_i^*}$$

where q is energy sales and the other variables are defined above (I use z as a generic independent variable here, including marginal price or income). It is interesting to compare these total elasticity estimates with the long-run consumption elasticities that are generated by the usual partial adjustment specifications. Depending upon the specification for 13e), TBV find long-run sales elasticities of income to be 1.00 - 1.30 and own-price (marginal) elasticities to be -.46 to -.90. The mean estimates are $e_y = 1.20$ and $e_p = -.60$. Such estimates accord with several long-run elasticity estimates (Anderson, HVS, MCT) from the single equation

partial adjustment models; however they are based upon explicit analysis of short-run and long-run behavior.

14) WILLIS (1977) MODEL

Wills (87) utilizes a short-run demand model similar to the Taylor, Blattenberger, Verleger/DRI (TBV) capacity utilization model 13d) and the Fisher and Kay-sen (FK) model. Wills also utilizes both marginal prices and fixed charges for the declining block rate tariff schedules as done by TBV and Acton, Mitchell and Mo-will. Wills tried a number of specifications; the specification for which he re-ports results is,

$$q = \alpha_0 + \alpha_1 PM + \alpha_2 Y + \alpha_3 PSFD + \alpha_4 HEAT + \alpha_5 WATER \\ + \alpha_6 STOVE + \alpha_7 COLOR TV + \alpha_8 FROST \quad 14)$$

where all variables are in logs and

q = kwh consumed/month/household

PM = marginal electricity price

Y = income

PSFD = percentage of customers living in single family dwelling

HEAT = a dummy variable, equal to one if consumption is in an all-elec-tric rate and zero otherwise

WATER = a dummy variable, equal to one if consumption is on a rate dis-counted for owners of electric water heaters and zero otherwise

STOVE = per single family dwelling ownership of electric stoves

COLOR TV = per single family dwelling ownership of color televisions

FROST = per single family dwelling ownership of frost-free refrigerators

The coefficient for the fixed consumer charge was never significantly different from zero; as a result, Wills subtracts the fixed charge from income and uses the the resulting net income as Y in the equation 14). The variables included in the

regression are clearly extremely disaggregated and refined; they result from consumption data for 39 Massachusetts electric utility districts and 57 residential rate structures. The short-run elasticity estimates conform with those of TBV and FK: the short-run own-price elasticity is $-.08$ while the short-run income elasticity estimate is $.32$.

A number of questions still remain for the Wills work. When HEAT and WATER are excluded, the explanatory power of the regression falls considerably and the coefficient estimates of PM and Y reverse signs. When saturation rates are used for space heating and water heating, the own-price elasticity is -1.33 which is unacceptably large. Further effort is required in assessing the usefulness of these dummies and saturation rates in capturing the presence of the appliance stock because they provide a simple substitute for the weighted appliance stock estimates used by TBV and FK. Those estimates utilize weights based upon "normal" usage; the problem is that normal usage will change with the independent variables. The utilization of saturation rates would avoid this difficulty.

15) WILSON (1971) MODEL

The Wilson model (85-86) focuses upon residential electricity demand and demand for six categories of household appliances. In the electricity model, 77 cities in 1966 provide the cross-section; 83 SMSA's in 1967 are used for the appliance demand. The electricity demand is reported here¹; it is given by

$$Q = b_1 + b_2P + b_3G + b_4Y + b_5R + b_6C + \epsilon \quad 15)$$

where

Q is the average electricity consumption per household

P = price of electricity (TEB for 500 kwh/Mo.)

¹The appliance modelling corroborates other efforts. The own price elasticity is significantly negative and less than -1 for all but home freezers. The price of natural gas is important in the equations for ranges, water heaters, and dryers.

- G = average gas price (cents per therm)
- Y = median family income
- R = average number of rooms per household
- C = number of degree days

The estimated elasticities are $e_p = -1.33$, $e_G = .31$ and $e_Y = -.46$. All are significantly different from zero. The own-price elasticity is quite large at -1.33 even for a long-run elasticity. The income elasticity is the wrong sign; it makes one wonder about the other estimates.

16) SUMMARY

In the early discussion of this section, three consumer decisions were identified for energy demand:

- The consumer decides whether to buy a fuel-burning consumer durable, capable of providing a particular consumer service (e.g. cooking, heating, lighting, air conditioning etc.)
- The consumer decides on the characteristics of the equipment he desires, including efficiency, technical characteristics and fuel type to be burned.
- Once the equipment is acquired, the consumer decides on the frequency and intensity of use.

These three decisions span short-run and long behavior.

A number of modelling techniques have been utilized to deal with one or all of these decisions. Three techniques predominate in the analysis reviewed above.

They are:

- Static long-run equilibrium formulations
- Dynamic partial adjustment of flow adjustment formulations
- Explicit multi-equation analyses of appliance stock utilization and changes in the appliance stock.

The models reviewed that are static, long-run equilibrium formulations include

those of Anderson (5,6), Halvorsen and Wilson. The dynamic partial or flow adjustment formulations are found in the analyses of Anderson (6); Balestra; Houthakker, Verleger, Sheehan; Mount, Chapman and Tyrrell; and Taylor, Blattenberger, Verleger/DRI. Analyses that focus explicitly upon short-run demand (given fixed appliance stocks) and/or long-run demand (through appliance stock changes) include those of Acton, Mitchell and Mowill; Fisher and Kaysen; Griffin; Houthakker; Wills; Taylor, Blattenberger, Verleger/DRI; and Cargill and Meyer.

The theoretical specification and the empirical implementation of the fifteen models have been discussed briefly above. Some comparative and critical comments were provided; however, greater critical review is required along the lines of the eight criteria of evaluation introduced in Section B. The following discussion critically summarizes and reviews the modelling efforts utilizing the eight model assessment criteria.

i) Proper identification of major market participants and the level of disaggregation required.

All of the models reviewed analyze electricity (gas and oil where appropriate) demand at the residential level except for Balestra who aggregates commercial and residential demand and Cargill and Meyer who aggregate the commercial, residential and industrial sectors. Such aggregation is inappropriate if one is interested in the residential sector specifically, given the data that is currently available. Usually total energy demand is analyzed on an annual or monthly basis. Either basis is appropriate; however the more temporally disaggregated the data, the better. Those analyses which deal with utilization of or changes in the appliance stock disaggregate residential stocks into a number of fuel-use categories including combinations of refrigerators, freezers, room air conditioners, water heaters, stoves, automatic washers, conventional washers, dryers, space heating

and central air conditioning.

All of the models disaggregated overall consumer utility/demand to energy demand alone; i.e. for fuels and fuel-burning appliances. Hence they assume separability. This assumption seems to be tenable.

ii) Proper identification and incorporation into variables in the model of policy issues and technological considerations for the major participants.

The major uses of the models discussed above include analytic understanding and policy assessment. The possible policy variables subject to analysis are long-run and short-run in nature. The short-run policy tools must deal with energy conservation and factors affecting appliance stock utilization (e.g. thermostat controls and other appliance use standards). In the long-run, variables should deal with new technologies, technological characteristics, efficiency standards and taxes and their effects upon changes in the stock of fuel-burning equipment.

The models discussed above include to varying degrees such variables as own and substitute prices (i.e. fuel operating costs), income, population, weather/climate variables, appliance stock variables and demographic variables. Which variables are incorporated into the models is detailed in Table 2. The population, weather/climate and demographic variables clearly are not easily used policy tools. More shall be said about these variables later. The own and substitute prices are clearly important policy tools that can be affected through such things as BTU taxes. All the models utilize own price; those analyses which do not include substitute prices suffer considerably. They are Balestra, Griffin, and Houthakker, Verleger, Sheehan. Fisher and Kaysen do not include gas price in short-run demand but they base its absence upon assumed zero cross-elasticity. The work of other analysts indicate such an assumption may be wrong. The remaining studies include gas as a substitute price; however, other substitutes include oil

and coal. Only Anderson (1973) includes these substitute prices. Furthermore although all studies include own-price, only Acton, Mitchell and Mowill; Taylor, Blattenberger, Verleger/DRI; and Wills explicitly deal with the declining block rate tariff structure through a marginal price and a fixed charge. The remaining analyses use average price, or TEB. This treatment of marginal and fixed charges will permit analysis of proposed electricity rate restructuring proposals such as rate leveling and rate structure inversion. Finally, none of the studies deal with the need for articulating gas prices through both a marginal rate and fixed charge. This absence introduces potential misspecification and biases the long-run gas price cross elasticity to zero.¹ It also limits policy analysis of rate restructuring for gas prices.

The presence of an income variable provides a limited policy tool. However greater analysis of appliance stock characteristics (efficiency, uncertainty of new technologies) and appliance capital costs are required in both the long-run and short-run. In the long-run, technological characteristics of old and new technologies and the cost of capital services must be taken into account. Fisher and Kaysen (FK), Mount, Chapman and Tyrrell (MCT) and Taylor, Blattenberger, Verleger/DRI (TVB) do include appliance prices; however, there exists interfuel comparison of technological characteristics which is crucial for long-run appliance stock demand by fuel-use category. In the short-run, the capacity utilization models of TBV and AMM utilize "normal" use to aggregate appliance stocks; changes in such normal use can be utilized in an ad hoc fashion to assess attractive conservation policies. However, explicit treatment of appliance stock efficiency is also needed to properly handle short-run demand and short-run policy possibilities.

Finally, some policy proposals such as peak load pricing options require

¹See Taylor, Blattenberger, Verleger/DRI (29).

seasonal and daily demand modelling. Few models have achieved that level of refinement. Acton, Mitchell and Mowill utilize monthly data and could be used to investigate changes in load duration curves on a seasonal basis. The model of Cargill and Meyer assesses hourly electricity demand and could be utilized to analyze the effects of hourly peak load pricing.

iii) Proper degree of geographical disaggregation

For the purposes of most policy analysis and simulation experiments, disaggregation to state level is sufficient. Most of the models in Table 2 are disaggregated to that level. More detailed and refined analytic results and policy assessments are possible if the geographical units are utility areas, meter read-book areas, cities and SMSA's (such as the works of Acton, Mitchell and Mowill, and Wills).

iv) Utilization of the appropriate behavioral models and underlying behavioral assumptions

As stated in the beginning of this summary, three sets of models have been utilized to deal with the short and long-run consumer decisions involved in energy demand. They include static equilibrium models, dynamic partial (flow) adjustment models and multi-equation separate treatment of the long-run and short-run. The static and dynamic models treat energy demand in aggregate without examining the relationship of such demand to the underlying fuel-burning appliance stock. The models implicitly assume some long-run equilibrium relationship of fuel demand to appliance stock, where both the fuel demand (stock utilization) and the stock are related to combinations of P_0 , P_S , Y , N , W , A , D and t in Figure 2. This is clearly a difficulty when potential policy actions and economic factors will affect appliance stock utilization rates.

Within this group of model types, the static equilibrium models (Anderson, Halvorsen and Wilson) are not designed to track short-run time series variation.

Anderson experiments with both dynamic and static formulations and finds that due to the relatively steady-state trending of the important variables in the 1960's, either the static or dynamic versions of demand models provided essentially the same parameter estimates and simulation performance. However this will not be the case for periods when such smooth trending in the economic time series is lacking, such as the 1970's. To take account of short-run disequilibrium effects, the dynamic models utilize lagged consumption. These models include Anderson (1973); Balestra; HVS; MCT; and TBV. By including the inertial effects of past consumption upon current consumption, these partial (or flow) adjustment models are definite improvements upon the static equilibrium formulation. Since energy demand is characterized by three consumer decisions (see overview of this section) that combine short-run and long-run behavior, the partial adjustment formulation permits explicit differentiation of the long-run and short-run responses.

In spite of the improved theoretical specification in the dynamic adjustment models, more explicit differentiation between and delineation of the determinants of long-run and short-run demand is required. The dynamic adjustment models still ignore the relationship of capital stock to fuel demand; they impose a constant relationship between the short-run and long-run elasticities for all exogenous variables ($e_{LR} = e_{SR}/1-\lambda$); they still do not permit explicit identification of long-run and short-run policy variables. The appropriate approach is explicit, separate multi-equation treatment of the long-run and short-run as found in AMM, FK, TBV, and Wills. Although each of these particular analyses has its own difficulties in terms of data and variable specification and/or exclusion, the group does represent the properly dichotomized behavioral specifications. The TBV analysis compares the long-run and short-run elasticities that result from a partial adjustment model and from a combined capacity utilization/capital stock model; the elasticities are not widely divergent. However, the combined multi-equation

analysis is much more refined in terms of data used and much more sound in terms of explicit behavioral representation and inclusion of policy variables.

v) Proper integration of the demand analysis into an overall energy and/or macroeconomic model

This criterion is appropriate for demand analyses that are part of a general equilibrium model. Most of the models reviewed here (except for Griffin) are not a part of larger models; hence, issues of proper integration and/or problems arising from improper integration are not relevant. In terms of using any of the models, all would require a set of assumptions about the exogenous variables in which the models are set. The more refined and complicated the model, the greater are the exogenous data requirements.

vi) Utilization of the proper data and statistical econometric techniques

This criterion proves to be a thorny one, particularly with respect to appropriate data. The appropriate statistical/econometric techniques are usually 2SLS, instrumental variables (IV), GLS, and/or an error components model. However in some cases, OLS has been used in generating results not widely different than those from a consistent technique (e.g., Mount, Chapman and Tyrrell long-run elasticities). Parameter estimation in the presence of serial correlation and a lagged endogenous variable is dangerous. If consistent techniques (IV, 2SLS) are not used, the parameter estimates can be worthless. Furthermore, even if consistent techniques are utilized the parameter estimates, particularly of the lagged endogenous variable, are extremely sensitive to assumed stochastic specification, sample period definition and variable definition.

It was not possible in this effort or in the original model-building efforts to subject these models to rigorous testing including forecasting, backcasting, estimation for sub-categories of data to test parameter estimate robustness, and examination of alternative variable specifications. TBV did some such analysis

by assessing the effects of different price specifications (marginal and fixed charge versus average revenue). They found little difference among them. However, Charles River Associates (CRA) subjected the Anderson, Halvorsen, HVS, and MCT models to rigorous model assessment along these lines. Their conclusions are disquieting. In the first place, CRA found little parameter robustness. Slight changes in the estimation period and definition of variables leads to widely differing parameter and elasticity estimates. For example, HVS generates price elasticity estimates which double as they move from one typical electric bill (TEB) to another. Likewise when CRA estimates the Anderson model for different regions to correct for regional differences (such as the presence of cheap electricity in the Pacific Northwest and TVA regions) the price elasticities fall from -1.3 to -.5. Secondly, CRA feels the long-run price elasticity is overstated in these four models for the following reasons: a) the problem of identification and specification of the rate structure bias the own price coefficient away from zero¹; b) aggregation of end use and cross-sectional (location/regional) variation overstate elasticities; c) gas and electricity price elasticity estimates are not consistent; d) a price elasticity greater than $|-1.0|$ cannot be plausibly explained in behavioral terms in light of realistic changes in the stock of consumer durables; and e) industry people claim that $|e_{LR}| < 1$.

These criticisms are aimed particularly at the static and dynamic adjustment formulations. The greater data refinement and disaggregation by end-use and better behavioral specifications inherent in the multi-equation capacity utilization/capital stock formulations of AMM, FK, and TBV avoid some of the difficulties.

¹It is therefore interesting that when TBV estimate the long-run price elasticity utilizing the theoretically correct two-part tariff specification with the usual partial adjustment model, they obtain an estimate of -.82 (see Table 2).

However one must still be careful to correct for cross-sectional variations (based upon climate, gas availability, regional availability of electricity in TVA and the Pacific Northwest) that will overstate elasticity estimates. Likewise one must attempt to avoid misspecification by dealing with the marginal and fixed charges inherent in the declining block rate tariff structures for gas and electricity.

vii) Provision of good documentation for the use of the energy demand modelling

viii) Provision for relatively easy accessibility and extensibility of the modelling effort

All 15 models score well under these two criteria. The data sources utilized by the analyses are usually well documented; alternative variable specifications and parameter estimates are presented.

Throughout the preceding discussions, the need is apparent to utilize the appropriate behavioral specifications, data, variables, and econometric/statistical techniques in order to properly analyze and quantify consumer response and behavior. Table 3 summarizes the resulting measures of consumer response for 14 models. For electricity demand, own-price long-run elasticity estimates vary from $-.52$ to -1.33 . The largest estimates are those of Halvorsen, Wilson, Anderson (1973) and MCT. When TBV utilize a better price specification, the elasticity bias away from zero is eliminated somewhat and $e_p = -.82$. The AMM and TBV analyses of capacity utilization indicate lower long-run elasticities, $-.12$ to about -1.0 . The short-run elasticities are generally much lower whether measured by a partial adjustment model (HVS) or by explicit capacity utilization/capital stock models (AMM and TBV). The cross-elasticity estimates indicate relatively uniform severe inelasticity, except for the estimates of AMM in the short-run. This is disquieting because AMM seems to have the best data and the theor-

TABLE 3: SUMMARY OF ELECTRICITY DEMAND ELASTICITY ESTIMATES

	OWN-PRICE		CROSS-PRICE		INCOME		OTHER
	L.R.	S.R.	L.R.	S.R.	L.R.	S.R.	
1) Acton, Mitchell and Mowell-AMM (1976)	-.70	-.35		.71		.38	
2) Anderson (1972)	-.91 -.88	-.58 -.77	.13 .17		1.13 .34	-.46	
3) Anderson (1973)	-1.12		.30				.27 oil price .12 coal price
4) Cargill and Meyer -CM (1971)		-.06 to -.58				≈ 0.0	
5) Fisher and Kaysen -FK (1962)		-.16 to -.25					
6) Griffen (1974)	-.52	-.06			.88	.06	
7) Halvorsen (1975)	-1.0 to -1.2		.05 to .09		.47 to .54		
8) Houthakker (1951)		-.9 to -1.04		.2 to .3		1.01 to 1.17	
9) Houthakker, Verleger and Sheehan-HVS (1974)	-1.0	-.089			1.6	.143	
10) Mount, Chapman and Tyrrell-MCT (1973)	-1.2	-.14 to -.36	.2		.21	.02 to .10	
11) Mount and Chapman (1974)	-1.17	-.31	.03 to .61	.01 to .16	.61	.16	
12) Taylor, Blattenberger and Verleger -TBV (1977)*	a) -.82 b) -.12 to -1.0 c)	-.08 -.06 to -.54 -.02 to .22		≈ 0.0	1.08	.10 .0004 to .38	-.02(SR) fixed elec- -.17(LR) tricity charge -.08(LR) fixed elec- tricity charge
13) Wills (1977)		-.08		.02 to .10		.32	
14) Wilson (1971)	-1.33		.31		-.46		

NOTES: *Taylor, Blattenberger, Verleger: a) Partial adjustment models, b) capital stock utilization model, c) capital stock model.

SOURCE: Table 1.

etical specification of short-run demand. Such a large estimate of short-run cross-price response seems implausible but merits further investigation. The income elasticity estimates vary from the improbable short-run estimates of 1.17 of Houthakker to the even more improbable long-run estimate of $-.46$ of Wilson. The partial adjustment estimate of TBV seems most believable.

The consumer responses to own and substitute prices summarized in Table 3 need to be complemented by response estimates to weather, fuel (gas) availability, capital stock prices and characteristics and policy variables. Such response estimates must result from the further analysis proposed in Section E.

D) INTERFUEL SUBSTITUTION DEMAND MODELS

Using the criteria of Section B in order to evaluate their ability to properly analyze both the nature of demand (in the short-run and long-run) and the competitiveness of new technologies, the individual fuel demand models introduced in Section C were found to exhibit varying degrees of sophistication with respect to behavioral specification, refinement of data and variable definition, utilization of econometric/statistical techniques and the inclusion of policy options and technological characteristics. One problem with all of these models, however, is that the possibilities for and effects of interfuel substitution are not explicitly examined. The models contain a number of cross-elasticities. However, to fully examine the long-run determinants of energy demand for all fuels, to explore the potential for market penetration of new fuel-burning technologies against each traditional fuel-burning technology and to adequately assess the desirability of each fuel in comparison with its potential substitutes, a model of interfuel substitution is required. The major premise of such interfuel substitution models is that the desirability (i.e. demand for) of any given fuel cannot be understood or predicted without explicitly predicting and understanding its desirability relative to all possible competitive fuels.

Five interfuel substitution models are examined here. They are:

- The Baughman/Joskow (BJ) Model
- The Federal Energy Administration Project Independence Evaluation System (FEA/PIES) Model
- The Oak Ridge/Hirst et al. (OR/H) Model
- The Anderson Model
- The Erickson, Spann and Ciliano (ESC) Model

The B/J and FEA/PIES models are more general equilibrium in their purview, modelling demand by all using sectors in addition to supply and market clearing. Only the demand modules of these models will be discussed in any detail here. The remaining

three models analyze demand alone.

The discussion here will proceed by introducing the models (or demand modules thereof). As in Section C, the critical summary will then summarize the evaluation of these models by the criteria introduced in Section B.

1) THE BAUGHMAN/JOSKOW (B/J) MODEL

The B/J Demand analysis is a module in the B/J Regional Electricity Model which also includes a Supply module and a Financial/Regulatory module. While all fuel types (coal, oil, gas and electricity) are examined, the principal focus of this model is the electric utility industry.

The energy demand module of the B/J Model consists of two major sectors: the residential/commercial sector and the industrial sector. I shall introduce them in some detail because the structures of several other interfuel substitution models are similar. The basic structures of these two sectors are presented in Figures 1A and 1B. Figures 2A and 2B present the equational specification of the sectors.

The energy demand behavior assumed in both sectors is step-wise rather than simultaneous; the behavioral specification begins with aggregate energy demand and then disaggregates it into state demand (for industrial) and particular fuel demands (for commercial/residential and industrial). The model of consumer behavior for the commercial/residential sector is summarized by B/J in [Baughman Joskow (13) p. 306]: "The consumer decision-making process is composed of two steps. First the consumer decides on a level of energy-using services that he desires based on the price of energy, the prices of other goods and services and household income. This decision defines the expected level of energy that will be consumed. The consumer then seeks to find a combination of fuels that will provide these services most cheaply."

The decision model for the industrial sector is separated into three decisions

FIGURE 1A : BAUGHMAN/JOSKOW DEMAND MODULE
RESIDENTIAL AND COMMERCIAL SECTOR

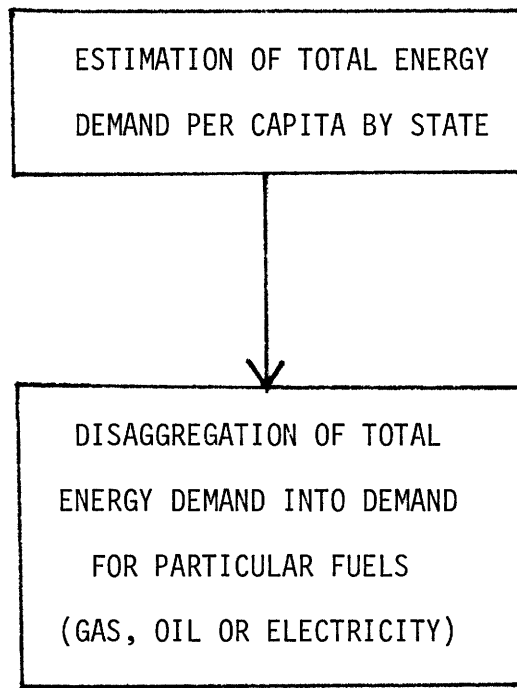


FIGURE 1B : BAUGHMAN/JOSKOW DEMAND MODULE
INDUSTRIAL SECTOR

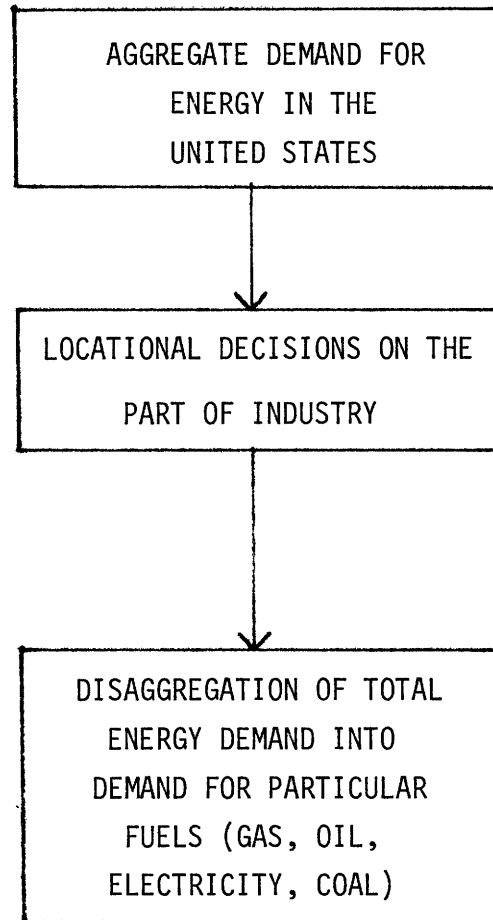


FIGURE 2A: RESIDENTIAL AND COMMERCIAL SECTOR, EQUATIONAL SPECIFICATION

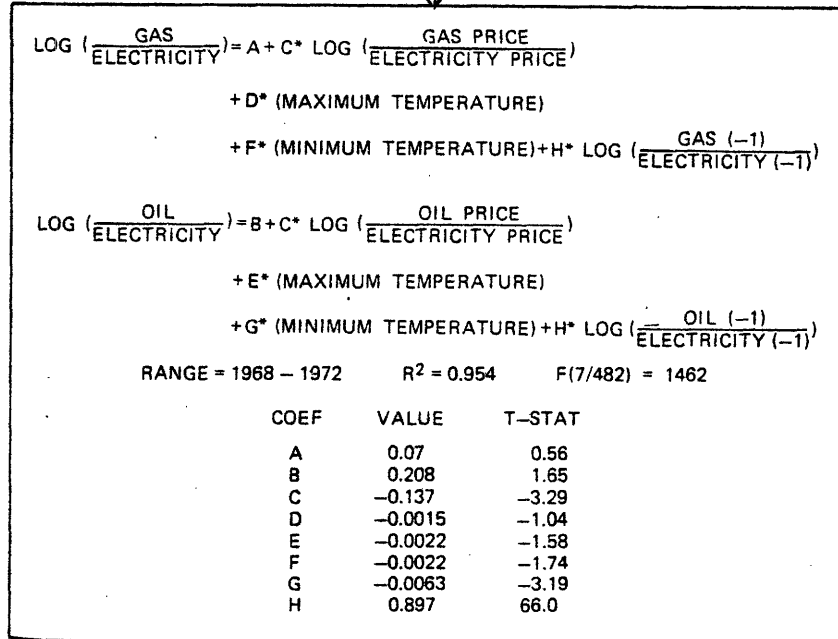
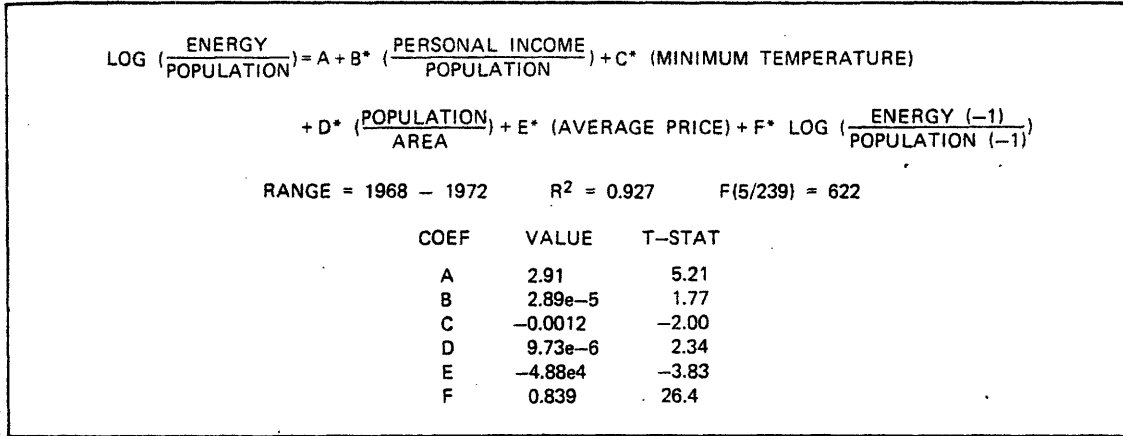


FIGURE 2B: INDUSTRIAL SECTOR, EQUATIONAL SPECIFICATION

LOG (ENERGY) = A + B * LOG (AVERAGE PRICE) + C * LOG (VALUE ADDED) + D * LOG (PRICE OF CAPITAL SERVICES)

RANGE = 1950 - 1972 R² = 0.961 F(3/19) = 182 D.W. = 1.86

COEF	VALUE	T-STAT
A	14.0	4.11
B	-0.239	-1.33
C	0.742	15.08
D	-0.270	-1.89

FIRST-ORDER AUTO CORRELATION COEFFICIENT = 0.337

LOG ($\frac{\text{ENERGY IN STATE } i}{\text{ENERGY IN CALIF.}}$) = A * LOG ($\frac{\text{AVERAGE PRICE IN } i}{\text{AVERAGE PRICE IN CALIF.}}$)

+ B * LOG ($\frac{\text{POPULATION IN } i}{\text{POPULATION IN CALIF.}}$)

+ C * LOG ($\frac{\text{ENERGY } (-1) \text{ IN } i}{\text{ENERGY } (-1) \text{ IN CALIF.}}$)

RANGE = 1968 - 1972 R² = 0.984 F(2/237) = 7506

COEF	VALUE	T-STAT
A	-0.156	-4.92
B	-0.047	3.24
C	0.927	54.1

LOG ($\frac{\text{GAS}}{\text{ELECTRICITY}}$) = A + D * LOG ($\frac{\text{GAS PRICE}}{\text{ELECTRICITY PRICE}}$) + E * LOG ($\frac{\text{GAS } (-1)}{\text{ELECTRICITY } (-1)}$)

LOG ($\frac{\text{OIL}}{\text{ELECTRICITY}}$) = B + D * LOG ($\frac{\text{OIL PRICE}}{\text{ELECTRICITY PRICE}}$) + E * LOG ($\frac{\text{OIL } (-1)}{\text{ELECTRICITY } (-1)}$)

LOG ($\frac{\text{COAL}}{\text{ELECTRICITY}}$) = C + D * LOG ($\frac{\text{COAL PRICE}}{\text{ELECTRICITY PRICE}}$) + E * LOG ($\frac{\text{COAL } (-1)}{\text{ELECTRICITY } (-1)}$)

RANGE = 1968 - 1972 R² = 0.945 F(4/730) = 3130

COEF	VALUE	T-STAT
A	-0.231	-4.31
B	-0.354	-6.80
C	-0.540	-8.23
D	-0.301	-7.13
E	0.856	58.9

[Baughman and Zerhoot (11), p. 8]: "First..., given a price of energy, one would expect individual decision makers to choose a mix of energy and non-energy inputs that would minimize the cost of production. The energy requirements would, consequently, depend on the cost of energy relative to the costs of other factor inputs and the total output of goods and services. A second, but related, level of decision making is the choice of location geographically within the United States. ...The third and final related decision is the choice of energy form (coal, oil, natural gas, or electricity) to be used."

All equations in Figures 2A and 2B approximate this decision making through a partial adjustment formulation in order to differentiate between the short-run and long-run. For the residential/commercial sector, total state energy consumption per capita is made a function of weighted energy price (weighted by consumption and end-use efficiency), income per capita, minimum temperature, and population density. Fuel split equations are then used to break out total energy consumption into shares represented by gas, oil and electricity. The binary share equations are functions of the two relevant fuel prices, maximum temperature, and minimum temperature. Pooled time-series cross-sectional data is utilized for 49 states over 1963-1972. However, the actual estimates reflect a 1968-1972 sample period; this sample period generates the most believable results in terms of implied short-term and long-term elasticities. One reason for this is that there is not enough variation in the price series over 1963-1967. An error components model is used to deal with the pooled data. Instrumental variables are used to avoid inconsistency in the presence of serial correlation and lagged endogenous variables.

For the industrial sector, lagged specifications in the total energy demand equation performed poorly; as a result, the lagged specification was dropped. In that equation, total national energy consumption is specified to be a function

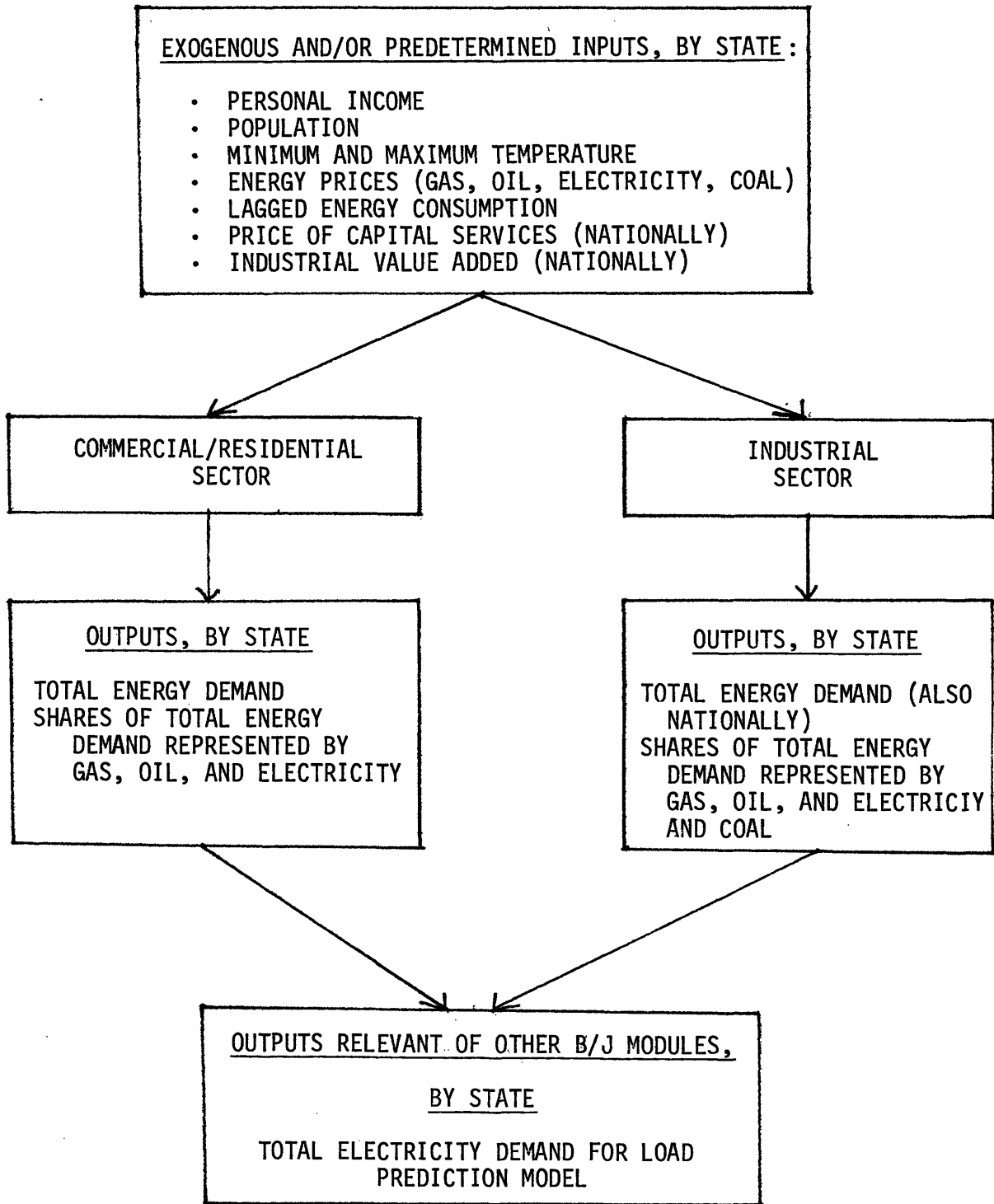
of an average energy price, value added in manufacturing and the price of capital services. National data for 1950-1972 are used. A second set of locational equations estimate the share of the total energy consumed in each state. Conditional logit split equations are used, making a state's share of the national total a function of relative energy costs in each state and relative state populations. A third set of fuel split equations disaggregates state fuel demand into components of coal, gas, oil, and electricity. Conditional logit is used, making the binary fuel share ratios functions of relative prices in a partial adjustment formulation. Pooled cross-section time-series (1963-1972) data is used. For the same reasons as the residential/commercial sector, the final estimates reflect the 1968-1972 period. An error components model is used to correct for the data pooling; 2SLS is used, given the use of a lagged endogenous variable in the presence of serial correlation.

Figure 2C indicates the inputs and outputs of the Demand module. Based upon exogenous estimates of income, population, climate conditions, relative energy prices and the prices of other factors, the Demand module estimates total energy demand and its components for the residential/commercial and industrial sectors. Furthermore the total electricity demand forecasts are utilized by the Load Prediction Model of the Supply module.

The documentation for the B/J demand module is extremely good and is found in the following six sources:

- M.L. Baughman and P.L. Joskow, "Interfuel Substitution in the Consumption of Energy in the United States: Part I, the Residential and Commercial Sectors," MIT-EL 74-002 (1974).
- M.L. Baughman and P.L. Joskow, "A Regionalized Electricity Model," Energy Lab. Report MIT-EL 75-005, December, 1974.
- M.L. Baughman and F.S. Zerhooth, "Interfuel Substitution in the Consumption of Energy in the United States: Part II: Industrial Sector," MIT-EL 75-007, April 25, 1975.

FIGURE 2C: DEMAND MODULE INPUTS AND OUTPUTS



- M.L. Baughman and P.L. Joskow, "The Effects of Fuel Prices on Residential Appliance Choice in the United States," Land Economics, February, 1975.
- P.L. Joskow and M.L. Baughman, "The Future of the U.S. Nuclear Energy Industry," The Bell Journal of Economics (Spring 1976).
- M.L. Baughman and P.L. Joskow, "Energy Consumption and Fuel Choice by Residential and Commercial Consumers in the United States," Energy Systems and Policy, Volume 1, #4; (1976).

The Bell Journal article (1976) contains the equational specifications that are most current and that have been discussed above. Baughman and Joskow (1974, 1975, and 1976) contain the residential and commercial modelling; Baughman and Zerhoot (1975) discusses the industrial sector modelling.

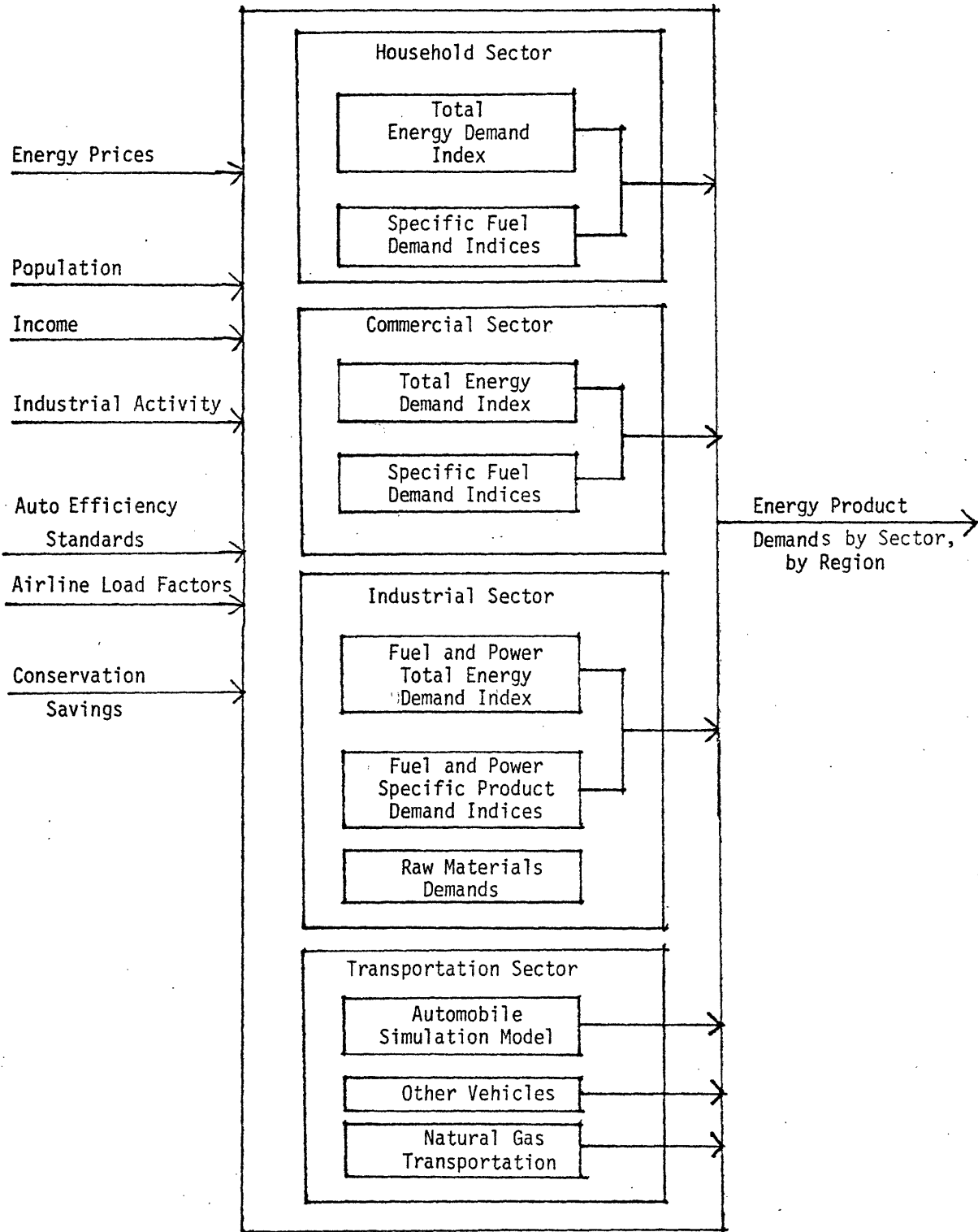
2) FEDERAL ENERGY ADMINISTRATION PROJECT INDEPENDENCE EVALUATION SYSTEM (FEA/PIES) MODEL

The FEA/PIES model was first developed by FEA to evaluate the effects of alternative projected energy conditions in the U.S. over the period 1973-1985. The model is a general equilibrium model which examines the effects of macro-economic conditions and energy price and policy assumptions upon energy supply and demand. The supplies and demands are equilibrated through a linear programming integrating model, which is a major contribution of the FEA/PIES effort. Furthermore, given equilibrium price and quantity solutions for twelve supplying regions and nine demand regions, the ex post effects of these solutions upon the macro-economy is assessed.

The Demand module of the FEA/PIES model has changed over the past several years. In the 1974 version¹, the model first estimated energy demands at the national level as a function of macroeconomic and technological factors. The national demands were then disaggregated to the census region level. Energy demand was estimated for the residential/commercial, industrial and transportation

¹Critically reviewed by J. Hausman (46)

FIGURE 3: PROJECT INDEPENDENCE EVALUATION
SYSTEM DEMAND MODULE



Source: Federal Energy Administration, National Energy Outlook, 1976, (35): Figure C-1.

sectors in a three step process: first, total demand was estimated as a function of weighted price (using energy shares as weights) and other economic/demographic variables.¹ Secondly, total electricity demand was estimated based upon the same variables plus mean degree days. Finally, traditional conditional logit share equations were utilized to predict the shares of the total fossil fuel demand (\equiv total energy demand - electricity demand).

In the 1976 version, the Demand module has been disaggregated to separate the commercial and residential sectors. The form of the current FEA/PIES Demand module is given in Figure 3. In the Figure, energy demand in each census region is shown to be approximated by the two step process B/J utilized in their residential/commercial demand analysis: first total energy demand is estimated; secondly, specific fuel demands are estimated. For each user sector total demand is estimated as a function fuel prices and sector activity in a partial adjustment formulation (i.e. with a lagged endogenous variable) in order to differentiate between the long-run and short-run. For example, for the residential sector,

$$\ln q_{it} = \alpha_i + \beta \ln PR_{it} + \gamma \ln Y_{it} + \lambda \ln q_{it-1} \quad 16a)$$

where q_{it} is the total energy quantity index of demand for region i in year t
 PR_{it} is the weighted energy price index (using fuel shares as weights)
 Y_{it} is the per capita income

Once total energy demand is estimated, the ratio of specific fuel demand to the total is estimated as a function of the relative price of the specific fuel (relative to the weighted average total energy price index) and the lagged value of the ratio of the specific fuel demand to the total (i.e. a lagged endogenous variable, again for the purpose of differentiating between the long-run and short-run). Thus, for example, for electricity in the residential sector

¹ See J. Hausman (46) for greater detail.

$$\ln \left(\frac{q_{e_{it}}}{q_{it}} \right) = \alpha_{ei} + \beta_e \ln \left(\frac{P_{e_{it}}}{PR_{it}} \right) + \lambda_e \ln \left(\frac{q_{e_{it-1}}}{q_{it-1}} \right) \quad 16b)$$

where q_e is the residential demand for electricity

P_e is the residential electricity price

e is the fuel specific subscript, here for electricity

q_i and PR_i are defined above

i and t are region and time subscripts

The individual fuels analyzed for the using sectors are indicated in Table 4.

Finally, the total price and quantity indices in each region are log-linear value-weighted averages of regional prices or quantities; that is,

$$\begin{aligned} \ln q_i &= \sum_k v_{ki} \ln q_{ki} \\ \ln PR_i &= \sum_k v_{ki} \ln P_{ki} \end{aligned} \quad 16c)$$

where
$$v_{ki} = \frac{P_{ki} q_{ki}}{\sum_j P_{ji} q_{ji}}$$

and P_{ki} is the price of the k th fuel in region i

q_{ki} is the consumption of the k th fuel in region i

q_i and PR_i are defined above (the time subscript has been dropped)

Equation 16a) is estimated utilizing pooled time-series/cross-sectional data (1960-1972) for the census regions). The price and activity variable coefficients are invariant with respect to time and region; however, regional specific intercepts are used. Likewise a regional specific first-order auto-correlation transformation was used. Equation 16b) was estimated separately for each of the nine census regions in similar fashion.

The documentation for the FEA/PIES model is found in:

- FEA, National Energy Outlook, 1976, FEA-N-TS/713, February 1976.
- FEA, Project Independence Blueprint, November 1974.

- Hausman, J., "Project Independence Report: An Appraisal of U.S. Energy Needs up to 1985," Bell Journal of Economics, Autumn 1975.

3) THE OAK RIDGE/HIRST et al. (OR/H) MODEL

The modelling efforts pursued by the group under Eric Hirst at Oak Ridge National Laboratory have been limited in focus to the residential demand for energy.¹ However while limiting their purview to residential demand alone and by combining econometric, economic and engineering modelling tools, the Oak Ridge group has developed a methodology rich in technological and policy detail. While the model is complicated and perhaps confusing upon first reading, it merits close scrutiny and understanding.

The OR/H model focuses upon four fuels (i = electricity, gas, oil and other) for three housing types (m = single family, multi-family and mobile home) for eight fuel end uses (k = space heating, water heating, refrigeration, food freezing, cooking, air conditioning, lighting and other). Use of fuel i is then determined in year t by housing type m for end use k as

$$Q_t^{ikm} = HT_t^m \cdot C_t^{ikm} \cdot TI_t^{ikm} \cdot EU_t^{ikm} \cdot U_t^{ik} \quad 17a)$$

where HT is the stock of occupied housing units;

C is the market share of households with a particular type of fuel-burning equipment;

TI is the thermal integrity of housing units (for space heating and air conditioning only);

EU is the average energy use for the type of equipment (i.e. efficiency);

and

¹Other efforts are being conducted directed at both industrial and commercial demand.

U is a usage factor.

The Oak Ridge group utilize a combination of demographic models (to explain and forecast housing stocks and flows), economic models (fuel demand and fuel share analyses) and technology models (to examine the relationship between capital cost and efficiency) to quantify the five components of equation 17a). The housing model predicts the number of households by the age of household head each year based upon population (for 7 age groups), per capita income and retirement rates for each housing type.¹ The model gives estimates of HT_t^m ; hence it estimates U and changes in the stock.

The fraction of households of type m that use fuel for end use k (C_t^{ikm}) is calculated by

$$C_t^{ikm} = \frac{(1-R^k)C_{t-1}^{ikm} HT_{t-1}^m + CN_t^{ikm} NU_t^{km}}{HT_t^m} \quad 17b)$$

where R^k is the equipment retirement rate for use k;

CN_t^{ikm} is the share of new equipment (NU) installed in t that uses fuel i for end use k for housing type m; and

NU_t^{km} is the number of new units installed during t that provide end-use k in housing type m.

CN, the market share of new units, is calculated from an equation of the form

$$\ln \frac{CN_t^{ikm}}{1 - CN_t^{ikm}} = A^{ikm} + \sum_{j=1}^3 (B^{ijk} \cdot X_t^j \cdot EUN_t^{jkm} \cdot TI_t^{jkm}) + \sum_{j=1}^3 (C^{ijk} \cdot PEQ_t^{jkm}) + D^{ik} \cdot Y_t \quad 17c)$$

¹For greater detail see E. Hirst et al., "An Improved Engineering -- Economic Model of Residential Energy Use," (49).

where X_t^j is fuel price for fuel j in year t ;
 EUN_t^{jkm} is new equipment energy use (efficiency) for equipment using fuel j in end use k in housing type m ;
 TI_t^{jkm} is average thermal integrity for housing type m using fuel j in end use k ;
 PEQ_t^{jkm} is new equipment purchase price for equipment burning fuel j in end use k ; and
 Y_t is per capita income.

A, B, C, and D are coefficients estimated by utilizing parameter and elasticity estimates from equations of the form:

$$\ln q_k = \alpha + \sum \gamma_i \ln P_i + \beta_1 \ln \text{PCI} + \beta_2 \ln \text{HDD} + \beta_3 \ln \text{COOL} \quad 17d)$$

$$\ln\left(\frac{S_k}{1 - S_k}\right) = \alpha_0 + \sum_i \gamma_i \ln P_i + \sum_j \beta_j \ln \text{PEQ}_j + \delta_1 \text{PCI} + \delta_2 \text{HDD} + \delta_3 \text{CDD} \quad 17e)$$

where q_k is the quantity consumed of fuel k /household.
 S_k is the share of the equipment stock using fuel k for each end use i .
 P_i are the own and cross-prices of fuels.
 PEQ_j are the equipment capital costs for alternative fuel-burning equipment.
 PCI is per capita income.
 HDD is heating degree days.
 COOL is mean July temperature.
 CDD is cooling degree days.

Equation 17d) is similar to the single fuel equations found in Section C while 17e) is similar to the logit share equation found in the discussions of interfuel substitution in Sections D1 and D2 above. The OR/H logit equations,

however, at least include capital costs. However, for space heating, only an oil equipment capital service price is used.¹ Additional economic/demographic variables were tested in equations 17e). Dynamic (lagged endogenous variable) and non-dynamic specifications were tested.

Based upon the parameter/elasticity estimates from equations 17d) and 17e) the OR/H utilizes an "Elasticity Estimator" to quantify A, B, C and D in 17c). The Elasticity Estimator is merely a set of semi-rigorous and/or ad hoc relationships developed to use the consumption elasticities (from 17d) and stock share elasticities (from 17e) to quantify the new equipment share (A), price (B), capital cost (C) and income (D) elasticities in 17c). While some of these relationships are arbitrary, this approach does provide a strong link in 17c) between the technological changes in EUN, TI and/or PEQ, economic changes in fuel prices and the fuel shares of new equipment purchases.

The EU terms (average annual equipment energy use) in 17a) are calculated as

$$EU_t^{ikm} = \frac{EUN_t^{ikm} CN_t^{ikm} NU_t^{km} + EU_{t-1}^{ikm} C_{t-1}^{ikm} HT_{t-1}^m (1 - R^k)}{C_t^{ikm} HT_t^m} \quad 17f)$$

where the terms of 17f) are all defined above. Likewise the thermal integrity TI terms, which are applicable only to space heating and air conditioning equations, are derived as in 17f). However TI can change through new housing units and retrofitting, both of which the model deals with deterministically.

Finally U, the usage term is given by

¹See Lin, Hirst and Cohn (60) for discussion of the logit estimates (equation 17e). Estimation of equation 17d) is discussed in Cohn, Hirst and Jackson, "Econometric Analyses of Household Fuel Demands" (28). The logit equations in 17e) improve upon the B/J equations because they are more generalized. See (43) and (45).

$$\ln U_t^{ik} = E^{ik} + F^{ik} \ln (X_t^i \cdot EU_t^{ikm} \cdot TI_t^{ikm}) + G^{ik} \ln Y_t + H^{ik} \ln U_{t-1}^{ik} \quad 17g)$$

where all variables are defined above and E, F, G and H are determined by the Elasticity Estimator in a manner similar to that discussed above for equation 17c). 17g) makes the intensity of household use (capital stock utilization) a function of incomes and operating costs of the equipment. Again, as found throughout the model, energy use depends upon both economic and technological factors.

The documentation for the OR/H model and technology assessment is contained in the following:

- Eric Hirst, et al., "An Improved Engineering-Economic Model of Residential Energy Use," Oak Ridge National Laboratory ORNL/CON-8 (April 1977).
- W.S. Chern, "Energy Demand and Interfuel Substitution in the Combined Residential and Commercial Sector," Oak Ridge National Laboratory, ORNL/JM-5557 (September, 1976).
- Cohn, Steve, Eric Hirst and Jerry Jackson, "Econometric Analyses of Household Fuel Demands," Oak Ridge National Laboratory, ORNL/CON-7 (March, 1977).
- W. Lin, E. Hirst and S. Cohn, "Fuel Choices in the Household Sector," Oak Ridge National Laboratory, ORNL/CON-3 (October, 1976).
- J. Moyers, "The Room Air Conditioner as an Energy Consumer," Oak Ridge National Laboratory, ORNL-NSF-EP-59 (1973).
- R. Hoskins and E. Hirst, "Energy and Cost Analysis of Residential Water Heaters," Oak Ridge National Laboratory, ORNL-CON-10 (June 1977).
- R. Hoskins and E. Hirst, "Energy and Cost Analysis of Residential Refrigerators," Oak Ridge National Laboratory, ORNL/CON-6 (January 1977).

4) ANDERSON MODEL

As discussed in Section C, Anderson has specified and estimated a number of single fuel demand models. In addition, he has dealt with appliance stocks differently than the usual conditional logit treatment. Anderson (6) focuses upon the shares of new installations (new installments + conversions + replacements) using a functional form approximating share s_i by f_i where

$$f_i \equiv \frac{q_i(\cdot)}{\sum_j q_j(\cdot)} \quad 18a)$$

where

$$\sum_i f_i = 1 \quad 18b)$$

and

$$q_i(\cdot) = a_i P_i^{b_i} v_i^{c_i} y^{d_i} Z_i. \quad 18c)$$

P_i is the price of energy i , v_i is the appliance price of fuel equipment, y is household income, and Z_i is a term including effects of all household-characteristic variables. Approximating s_i (share of new installations using fuel i) by $f_i \cdot u_i$, where u_i is an error term, Anderson generates $m - 1$ equations of the form

$$\frac{s_i}{s_m} = \frac{q_i(\cdot)}{q_m(\cdot)} \frac{u_i}{u_m} = \frac{a_i}{a_m} P_i^{b_i} P_m^{-b_m} v_i^{c_i} v_m^{-c_m} \cdot y^{d_i - d_m} \cdot \frac{Z_i}{Z_m} \frac{u_i}{u_m} \quad 18d)$$

where there exists m possible fuels to be used. Anderson uses log-linear forms of 18d) and Zellners' seemingly unrelated equations estimating technique. Anderson uses state cross-sectional data on home-heating for 1970 and 1960/1970 and ultimately estimates equations of the form

$$\ln \frac{s_i}{s_m} = a_{im}^0 + a_i \ln P_i + a_m \ln P_m + a_{im}^1 YPH + a_{im}^2 \ln HS + a_{im}^3 SHU + a_{im}^4 NuHu + a_{im}^5 WTEMP + u_{im} \quad 18e)$$

$$i = 1, \dots, m - 1$$

where s_i, s_m are the shares of home heating installations using fuels i and m
 P_i, P_m are the fuel prices

- YPH is annual income for household
HS is household size (persons/household)
SHU is the fraction of total housing that is single detached housing units
NuHu is the fraction of total housing that is non-urban
WTEMP is mean December temperature

Similar equations with different independent variables are estimated for water heating installations, cooking installations, washing and drying installations, air conditioning, food freezing, dishwashing and television installations. The resulting elasticity estimates are discussed in the summary to this section.

In equation 18d) Anderson appropriately dichotomizes the short-run and long-run energy demand decisions by focusing upon the determinants of consumer demand for changes in the stock of residential appliances. Equation 18d) is well-specified to analyze the determinants of that demand; it includes fuel operating costs, income effects, demographic effects and the technical characteristics of the appliances (summarized by appliance prices). Unfortunately, the estimated equation does not include the appliance prices.

The single source for the model is

- K. Anderson, "Residential Energy Use: An Econometric Analysis," Rand Corporation, R-1297-NSF (October 1973).

5) ERICKSON, SPANN AND CILIANO (ESC) MODEL

The ESC model is interested in both usage and substitution in energy demand in the combined residential and commercial sector. Rather than using the traditional log shares logit formulation however, ESC model fuel shares in new construction as

$$s_{it} = a + bx_t \quad 19a)$$

where s_{it} is the share of new construction using fuel i in time t , and x_t is the

vector of exogenous variables. In order to model actual demand, ESC model average usage per consuming unit as

$$u_{it} = a^1 + b^1 z_t \quad 19b)$$

where z_t are exogenous. Since

$$S_{i,t} = S_{i,t-1} + s_{it} - l_{it} \quad 19c)$$

where S_{it} is the market share of fuel i in time t , and

l_{it} is the loss rate of market share for i and t .

The residential and commercial demand D_{it} in time t for fuel i is given by

$$D_{it} = S_{it} * N_t * u_{it} \quad 19d)$$

where N_t is the total number of households. Substituting, one has

$$D_{it} = (S_{it-1} + a + bx_t - l_{it}) (a^1 + b^1 z_t) N_t \quad 19e)$$

For the home heating share equations, ESC estimate equation 19a) for gas and oil as follows:

$$\begin{aligned} \ln s_{gas} = & a_0 + a_1 P_g/P_o + a_2 P_g/P_e + a_3 AC + a_4 u + a_5 Y \\ & + a_6 D1 + a_7 D2 + a_8 D3 + a_9 D4 + a_{10} S2 \end{aligned}$$

$$\begin{aligned} \ln s_{oil} = & b_0 + b_1 P_o/P_g + b_2 P_o/P_e + b_3 AC + b_4 u + b_5 Y \\ & + b_6 T_1 + b_7 D1 + b_8 D2 + b_9 D3 + b_{10} D4 + b_{11} S2 \end{aligned}$$

where s_{oil} = The ratio of oil burners installed in new dwelling units to total new construction

s_{gas} = Natural gas heating customers added via new construction divided by total new construction

P_o = The average real price of fuel oil in dollars per barrel to the residential market sector

P_g = The average real price of natural gas in dollars per cubic foot to the residential market sector

- U = An index of urbanization
- Y = Real income per capita
- S1 = The percent of new construction that is one or two-family dwelling units
- S2 = The percent of new construction that is four-family dwelling units or less
- T1 = Winter temperature
- AC = The number of private one-family homes sold with air conditioning.
- D1 to D4 = A set of dummy variables with D1=1 for Louisiana; D2=1 for Oklahoma; D3=1 for Texas; and D4=1 for New Mexico.
- Pe = The average real price of residential electricity

6) SUMMARY AND OVERVIEW

It will be recalled from Section C that there are three consumer decisions that span the short-run and long-run (see p. 12). The single fuel models were found to deal with these differences in one of three ways: 1) not at all; 2) implicitly, through a partial adjustment formulation; or 3) explicitly, through multi-equation capital stock/capital utilization analyses. The interfuel substitution models likewise deal with the differences in several ways. B/J and FEA/PIES utilize the partial adjustment/lagged endogenous variable formulation to differentiate between the short-run and long-run. The OR/H model specifies annual fuel demand in equation 17a) by explicitly analyzing the size of the housing stock, the fuel shares of the stock and changes in the stock of several appliance types, the thermal integrity of the housing stock, the efficiency of new and old appliances and capital utilization. The equation incorporates past decisions built into the appliance stock in addition to the consumer decisions (fuel shares) built into the additions to the appliance stock (i.e., long-run decisions). The

OR/H model deals with short-run intensity of use decision explicitly through EU. Thus OR/H deals explicitly with all three of the consumer decisions. However, the model bases the parameters of analysis upon traditional static and dynamic partial adjustment fuel share formulations (7e) and energy demand (7d) equations. These traditional results are utilized for estimates of explicit short-run and long-run elasticities; however, the estimation is ad hoc. Both Anderson and ESC model shares in changes in the appliance stock, thereby dealing with decisions 1 and 2 explicitly.

A number of the corresponding long-run and short-run elasticity estimates for these studies will be presented below in the summary comments. The comments will follow the eight criteria of evaluation found in Section B.

i) Proper identification of the major market participants and the level of analytic disaggregation required.

The B/J demand module focuses upon the aggregated commercial/residential and industrial sectors, while ignoring transportation demand (unlike the FEA/PIES model). B/J assesses demand for coal, oil, gas and electricity. Electric utility demand is analyzed elsewhere in the B/J model. The exclusion of transportation demand is a potential problem for several reasons. Its exclusion will understate total demand for alternative fuels. Secondly, its exclusion will limit the policy analysis use of the model by making it difficult to assess proposals for rapid transit and electric autos. FEA/PIES focuses upon residential, commercial, industrial and transportation sectors separately. Furthermore the fuels examined are disaggregated to a finer level of detail as indicated in Table 4. OR/H focuses upon residential demand for four fuels (gas, oil, electricity, other) for eight fuel uses in three housing types. Anderson analyzes residential demand for six fuels¹ for a number of fuel uses. ESC focus upon residential and commercial

¹Gas, oil, electricity, bottled gas, kerosene, coal.

TABLE 4 : FUELS MODELED JOINTLY BY SECTOR

RESIDENTIAL SECTOR

Electricity
Natural Gas
Distillate Oil
Kerosene
Liquid Gases

COMMERCIAL SECTOR

Electricity
Natural Gas
Distillate Oil
Residual Oil

INDUSTRIAL SECTOR

Electricity
Natural Gas
Distillate Oil
Residual Oil
Kerosene
Liquid Gases
Coal

home heating demand.

The lack of disaggregation of the two sectors in the B/J model is not a serious difficulty given the analytic aims of the authors. B/J appear to have been most interested in analyzing fuel supply and the financial/regulatory environment of the electric utility industry. As a result, they looked to close the demand side of the model with an aggregate energy demand module that provided little in the way of disaggregated policy analysis. However, greater disaggregation would be necessary if any short-run conservation policies and long-run demand for new technologies were to be analyzed with the demand module. For example appliance efficiency taxes, appliance efficiency standards, heating thermostat controls and the technical characteristics of new technologies are use-specific for the residential, commercial, and industrial demands. Incorporation of such technological and policy variables would require use-specific analyses. Such use-specific analysis would also permit differentiation of use-specific price elasticities. For example, in Figure 4A, aggregate B/J commercial/residential short-run price elasticities are presented while Figure 4B presents B/J elasticity estimates for four specific residential uses. As is seen in the two figures, disaggregation provides widely different estimates of the relevant elasticities.

The FEA/PIES model provides greater disaggregation by breaking out the residential and commercial sectors and by further disaggregating the fuels used by the residential, commercial and industrial sectors (see Table 3). Thus FEA/PIES provides greater refinement for assessing policy proposals for the residential and commercial sectors separately. It furthermore permits refined assessment of more fuel-specific policies, such as BTU taxes on alternative fuels. The OR/H focuses upon residential demand and provides a high degree of disaggregation by fuel, fuel use and housing type. Furthermore, it is the only model that deals explicitly with such engineering/policy considerations as the thermal integrity

FIGURE 4A : AGGREGATE RESIDENTIAL AND COMMERCIAL SECTOR
SHORT-RUN SHARE ELASTICITIES

	Pe	Po	Pg
S_e	-0.800	0.284	0.514
S_o	0.414	-0.929	0.514
S_g	0.414	0.284	-0.698

Source: Baughman and Joskow (13)

FIGURE 4B : DISAGGREGATED SHORT-RUN FUEL SHARE ELASTICITIES FOR PARTICULAR RESIDENTIAL USES

HOUSE HEATING

	P_e	P_g	P_o
Electricity	-2.08	2.12	3.30
Gas	.23	-1.48	3.30
Oil	.23	2.12	-7.21

WATER HEATING

	P_e	P_g	P_o
Electricity	-2.08	2.87	2.91
Gas	1.14	-2.28	2.91
Oil	1.14	2.87	-2.74

COOKING FUEL

	P_e	P_g
Electricity	-1.18	1.05
Gas	1.15	-1.03

CLOTHES DRYERS

	P_e	P_g
Electricity	- .58	.53
Gas	2.05	-1.99

Source: Baughman and Joskow (9)

(TI) of the residential structures, the average energy use (EU) for types of equipment (i.e. efficiency), a usage factor (U) for the equipment (i.e. short-run demand given capital in place) and capital cost characteristics of alternative fuel-burning equipment [see equation 17a) and 17e)]. Thus the OR/H model provides the richest specifications and disaggregation for policy purposes; appliance efficiency taxes and standards, heating thermostat controls and the capital cost and technological characteristics of new technologies could be introduced into the model and the effects upon residential energy demand assessed.

The Anderson demand analysis is disaggregated by eight fuels for residential demand; however the independent variables available for policy analysis are only operating costs. Hence as with B/J there is little room for more extensive policy analysis. The ESC model examines only gas and oil explicitly (electricity share is a residual) and there exist no real policy variables except operating costs.

Of the models reviewed, only B/J and FEA/PIES assess industrial demand. For this sector, greater disaggregation along two-digit SIC's for process and comfort use would be extremely useful. Such disaggregation would permit the analysis to be technology/process specific and hopefully permit the introduction of capital stock characteristics, particularly fuel-burning equipment characteristics. However, the data problems are significant and it is not clear that such disaggregation is possible at the moment without an onerous data gathering effort.

ii) Proper identification and incorporation into variables in the model of policy issues and technological consideration for the major market participants.

As mentioned above, the level of aggregation in the B/J and FEA/PIES demand modules precludes the efficient incorporation of several use-specific technological characterizations and policy variables. This is a difficulty for properly assessing the three consumer decisions spanning the short-run and the long-run and for assessing new technologies. However, in spite of the aggregation, other

policy variables could have been incorporated including, for example, average appliance efficiency, average fuel efficiency and capital costs of alternative fuel-burning equipment. The only policy variable available to the analyst in the B/J, FEA/PIES, and ESC demand modules is the operating cost of alternative fuels -- an extremely limited policy variable. No technological characteristics of alternative fuels and their relevant equipment are included. The availability of a single price-based policy variable ignores the use-specific policy options mentioned above: appliance efficiency taxes and standards, thermostat controls, speed limits. Furthermore, while B/J and FEA/PIES utilize a partial adjustment formulation in order to differentiate between the short-run and long-run, this formulation still ignores the important differences between short-run and long-run policy options: in the short-run, (fixed stock of capital and fuel-burning equipment) conservation and capital utilization policies are relevant while in the long-run, (variable stock of capital and fuel-burning equipment) policies aimed at new technologies and improved appliance efficiency are important.

The OR/H model does the best job of providing a framework for dealing with the technological and cost characteristics of old and new technologies and specific policy proposals within a well specified dichotomization of the short-run and long-run behavioral differences.

As a specific example of policy analysis, B/J utilize the model to assess several electric utility policy proposals in Joskow and Baughman (58). The policy possibilities include higher air pollution restrictions, peak load pricing, decreased nuclear plant lead times, a nuclear moratorium, higher costs of capital, and higher costs of uranium ore and enrichment. All of the policy proposals have important and far-reaching effects. However, the simulation of several proposals, particularly peak load pricing policies, requires a level of detailed sophistication lacking in the average electricity price generated in the Regulatory-Fi-

nancial module of the B/J model and exogenously applied to the demand module. One example of a more detailed analysis is the multi-tariff work done by Taylor, Blattenberger, Verleger/DRI (reviewed in Section B).

iii) Proper degree of geographical disaggregation.

All five models reviewed utilize either cross-sectional or a pooled time-series of cross-sections where the cross-sections are by states. Such state detail in the data provides the ability to test and simulate regional homogeneity. Hence the models possess the data and techniques to be quite regionally disaggregated. Furthermore, the B/J and FEA/PIES models do simulate on a regional basis (for Census regions). Such regional disaggregation is appropriate for most policy analysis.

iv) Utilization of the appropriate behavioral models and underlying behavioral assumptions.

As mentioned in the preceding paragraphs, there exists important behavioral and policy differences for short-run and long-run energy demands which require more refined behavioral specifications, technological characterizations and policy variables than fuel prices alone. The important differences between the short-run and the long-run argue for explicit multi-equation analysis of the separate phenomena. The B/J and FEA/PIES demand modules deal with the difference by utilizing a standard single equation partial adjustment formulation. Such a partial adjustment formulation is an acceptable first-cut technique; however, it has difficulties. In addition to the lack of specificity of the differences between the long-run and short-run (mentioned under criteria ii) the partial adjustment formulation's use of a lagged endogenous variable presents econometric difficulties. In the presence of a serial correlation, potential parameter estimate inconsistencies arise. Furthermore, the lagged adjustment parameter estimate is extremely sensitive to sample period and stochastic specification.

Since we are particularly interested in the difference between short-run and long-run consumer reactions and since the parameter estimated for the lagged endogenous variable is crucial in estimating the difference between short-run and long-run responses, these estimated differences will also be quite sensitive to the sample and the assumed stochastic specification.

A second problem involves the behavioral assumptions underlying the B/J and FEA/PIES demand modules. Total national demand (for the B/J industrial sector) or state energy demand (for the B/J and FEA/PIES commercial and residential sectors) are estimated, and these totals are disaggregated into location and particular fuels assuming cost-minimizing behavior on the part of the relevant participant. Such sequential "trickle-down" decision making implies that consumers decide on the total energy demand independent of their location and their capital stock and fuel-burning equipment. Once these consumers decide on total energy needs, they decide on location (for industry in B/J) and type of fuel to be utilized (for industrial, commercial and residential in FEA/PIES and residential/commercial in B/J).

Such assumed decision-making may generate believable results at the aggregate residential/commercial sector level. However, at the disaggregated use-specific level such trickle-down decision making can lead to contradictions. The reason is that consumers will cost minimize in choosing alternative locations and/or fuels in the long-run when changes in the stock of capital and fuel-burning equipment are possible. In the short-run, relocation and interfuel substitution are nearly impossible. The contradictions can arise in B/J when the share equations are applied to total energy demand and the predicted fuel shares imply appliance stock changes that are larger than possible.

The direction of causation in these models seems to be reversed. Rather than modelling the aggregate and breaking out the components, it seems that

explicit micro modelling of the short-run and long-run demands for alternative fuels and equipment should be performed and then aggregated to the totals.

The OR/H, Anderson and ESC models improve upon this treatment. They do not utilize a partial adjustment formulation to differentiate the long-run and short-run. Rather, all three models deal with the fuel shares in the changes in the appliance stock, where consumer decisions are actually exerted. The OR/H analyzes demand at the micro level (for fuel, fuel use and residential structure) and aggregates rather than assuming a "trickle down" decision process. It also provides the best example of explicit multi-equation analysis of short-run and long-run issues including: short-run demand for fuels given appliance stocks; and long-run demand for old and new technologies in the additions to the appliance stock, based upon operating costs, capital costs and appliance efficiencies.

The utilization of conditional logit (by B/J, FEA/PIES and OR/H) or other share analysis techniques (Anderson, ESC) presents varying problems. The conditional logit formulation utilized by B/J in the fuel split equations for both sectors is inappropriate for the following reasons: the imposition of constant cross-elasticities [see Baughman and Joskow ((9), (12), (13)), Domencich and McFadden (32), Hartman (43), Hartman and Hollyer (45)]; implied misspecification [see Hartman (43) and Hartman and Hollyer (45)]; excluded variables; and the restrictive underlying model of individual choices [see Hartman (43) and Hartman and Hollyer (45)]. The 1974 FEA/PIES model imposed constant cross-elasticities [see Hausman (46)] and suffered from the same problems listed above. The 1976 FEA/PIES model avoids some of these difficulties but forces cross-elasticities to be zero (see equation 16b) while also suffering from excluded variables (cross-prices and capital costs to name a few - see Hartman and Hollyer (45)) and the restrictive model of individual choice [see Hartman and Hollyer (45)].

To indicate the effects of some of the difficulties Figure 5 compares elas-

FIGURE 5 : COMPARISON WITH ALTERNATIVE ANALYSES : PRICE ELASTICITIES
OF FUEL SHARES, RESIDENTIAL SPACE HEATING

UNCONSTRAINED CROSS ELASTICITIES

	Log-Log			Semi-Log		
	a) <u>Lin, Hirst and Cohn</u>			a) <u>Lin, Hirst and Cohn</u>		
	Pe	Pg	Po	Pe	Pg	Po
	Space Heating					
Electricity	-2.63	0.44	1.37	-3.19	0.38	1.09
Gas	0.39	-1.57	0.03	0.57	-1.33	0.03
Oil	0.03	3.51	-1.09	-0.18	2.95	-1.01

CONSTRAINED CROSS ELASTICITIES

	b) <u>Anderson</u>			c) <u>Baughman & Joskow</u>		
	Pe	Pg	Po	Pe	Pg	Po
	Space Heating					
Electricity	-2.04	2.21	0.55	-2.08	2.12	3.30
Gas	0.17	-1.80	0.55	0.23	-1.48	3.30
Oil	0.17	2.21	-1.58	0.23	2.12	-7.21

Sources

- a) Lin, Hirst and Cohn (60)
- b) Anderson (4)
- c) B/J (9)

ticity estimates of B/J with those of Anderson (4) and OR/H [Lin, Hirst and Cohn (60)]. The conditional logit-formulation of B/J and Anderson methodology impose constant cross-elasticities. The Lin, Hirst and Cohn analyses utilize a more general logit formulation which avoids the misspecification [Hartman (43)] and permits the estimation of differential cross-elasticities, as are documented in Figure 5.

Furthermore, the fuel split equations for B/J and FEA/PIES (34 and 35), as stated above, include only fuel costs; hence they ignore capital costs, non-price characteristics of alternative fuels, personal characteristics of the fuel-choosing population and new technologies. ESC and Anderson ignore capital costs but include personal and demographic factors. Figure 6 indicates fuel share elasticities with capital costs included. Some elasticity estimates are the wrong sign; some of these incorrect signs result from coefficients not significantly different from zero. The point to be made is the inclusion of excluded variables does change price elasticity estimates considerably (compare Figure 5 with Figure 6).

For comparability of the analyses, the elasticities in Figures 4-6 have been based upon a logit specification without a partial adjustment formulation; that is logit share equations are applied to the stock of appliances. If a partial adjustment formulation were built into all of them, the results should differ in the same fashion as indicated in Figures 4-6. However, the underlying model of consumer choice is most valid when applied to changes in the stock of appliances. Figure 7 presents for comparison, fuel share elasticities for changes in the housing/appliance stock. As Figure 7 indicates, the elasticity estimates again differ considerably from those in Figures 4-6. OR/H, Anderson and ESC do analyze changes in the equipment stock.

In the face of such alternate estimates one must seek a model that best ap-

FIGURE 6 : RESIDENTIAL HOME HEATING FUEL SHARE ELASTICITIES
WITH CAPITAL COSTS INCLUDED

	<u>Share Electricity</u>	<u>Share Oil</u>	<u>Share Gas</u>
Pe	-3.86	-1.47	1.31
Po	2.34	-0.521	0.136
Pg	0.278	1.69	-1.13
CAPe	-10.4	4.45	-2.01
CAPo	10.3	-34.4	21.7
CAPg	-1.82	31.4	-20.5
AV	0.865E-01	-1.66	1.08
PCI	0.954	-0.261	0.867E-01
TEMP	-0.558E-01	0.578	-0.375

Source:

Hartman and Hollyer (45)

FIGURE 7 : SHARE ELASTICITIES FOR CHANGES IN THE HOUSING STOCK,
HOME HEATING

	Pe	Pg	Po	PCI
Se	-1.567	1.286	.245	-1.203(0)*
Sg	.730	- .611	- .437(0)*	.568(0)*
So	2.491	4.037	-10.829	-1.654(0)*

*Elasticity value if parameters not significantly different from zero
are set to zero.

Source: Hartman and Hollyer (45)

proximates consumer choice without imposing misspecification or severe restrictions upon the behavioral estimates.

While the preceding discussion was directed primarily at residential and commercial demand modelling, there exist some difficulties in the two models that address industrial demand modelling (B/J and FEA/PIES). Since the FEA/PIES model treats industrial demand the same as commercial and residential demand, the same problems exist as discussed above. Furthermore, both B/J and FEA/PIES ignore more detailed production analysis. Admittedly, at the time the B/J and FEA/PIES (34) analyses were performed, some of the more sophisticated production/cost duality approaches had not been popularized [Econometrical International (33)]. However, there existed enough of a literature to more credibly approach the problem. The prices of all other factors of production are ignored in Baughman and Zerhoot (11) and in FEA/PIES. Capital service prices are at least added in Joskow and Baughman (58). However, there remain serious inadequacies in the industrial demand modelling. The B/J and FEA/PIES models have not adequately dealt with the details of industrial production technology, even at an aggregate level, nor its formal relationship to derived demand.

Furthermore, while FEA/PIES does differentiate between long-run and short-run demand through a partial adjustment formulation, the national industrial energy demand analysis of B/J does not. Baughman and Zerhoot (11) claim that attempts to build in lagged responses were unsuccessful. It is claimed an Almon lag specification was not attempted because it would only worsen multi-collinearity compared to unconstrained lag estimation. That is, unfortunately, not true; the use of the Almon lag should lessen multi-collinearity problems. Furthermore, the Koyck lag specification implies an adjustment time of two years: that is too short to be believable. As a result, Baughman and Zerhoot (11) and Joskow and Baughman (58) do not use a lag specification, implying price response

is immediate (i.e. within a year) for aggregate energy demand. That is not a particularly useful or believable assumption to impose.

v) Proper integration of the demand module into an overall energy and/or macroeconomic model.

All five models require the specification of exogenous variables in order to do policy simulation. However, only the B/J and FEA/PIES are general equilibrium in the sense that they deal with supply and demand and market clearing for all sources and uses of the fuels analyzed. The FEA/PIES model utilizes a linear programming integrating model which recursively converges to a market equilibrium solution for all supplies and demands. This provision is a major innovation and an extremely desirable feature of the model. Its desirability can be assessed by comparing this procedure with the B/J model. The B/J demand module is not solved simultaneously with the full model. Thus, while endogenous to fuel supply sectors, alternative fuel prices are exogenous to the demand module. As a result, non-marginal shifts in demand for alternative fuels are not permitted to "play back" upon supply. In essence, supply is assumed infinitely elastic at the exogenous price.

The failure to deal with such simultaneities for non-marginal demand shifts could generate serious errors in the analysis of the impacts of particular policies. For example, policies aimed at large regional (say New England) shifts of demand to coal must take account of the bottlenecks caused by the transportation (railroad) infrastructure. Non-marginal demand shifts to coal could push demand beyond the short-run transportation bottleneck, thereby making the short-run supply price infinite. Likewise, non-marginal shifts in gas demand in New England have historically led to imported LNG from Algeria at a supply price well above domestic gas. The assumption of infinitely elastic supply at a constant price ignores these realities and distorts projected fuel demands as a result.

vi) Utilization of proper data and statistical/econometric techniques

The econometric techniques utilized by the five interfuel substitution models are more or less state of the art. Two stage least squares (2SLS) is utilized in the presence of serial correlation and a lagged endogenous variable; however, the models do not document the instruments used. However, it must be stated that the simulation results are, in general, extremely sensitive to model specification, variable definition and sample period of estimation. Figures 8A-8D demonstrates simulation differences between the B/J and FEA (34) model for fuel price scenarios outlined in Figure 8A. Figures 8C and 8D indicate several wide divergences and the reasons.

vii) Provision of good documentation for the use of energy demand modelling.

All five models score well under this criteria.

viii) Provision for relatively easy accessibility and extensibility of the modelling effort.

All five models are accessible. However B/J, FEA/PIES and OR/H are quite large: hence while accessible, the extensibility depends upon how complicated the desired changes are.

FIGURE 8A: REAL PRICES (1974 DOLLARS) USED FOR B/J AND
FEA INDUSTRIAL SIMULATIONS

CASE I - F.E.A. \$11 per barrel				
	Oil Price (\$/Bbl)	Natural Gas Price (¢MCF)	Coal Price (\$/ton)	Electricity Price (¢/Kwhr)
1975	6.70	64.2	10.44	2.39
1980	10.34	64.2	10.44	2.46
1985	10.86	64.2	10.44	2.27
CASE II - F.E.A. \$7 per barrel				
1975	5.50	64.2	10.44	2.39
1980	7.00	64.2	10.44	2.46
1985	7.00	64.2	10.44	2.27
CASE III - No O.P.E.C. (2% per year real increase)				
1975	4.16	62.4	7.80	1.96
1980	4.59	68.9	8.62	1.99
1985	5.07	76.1	9.52	1.87

Oil is average price at the wellhead

Gas is average price at the wellhead

Coal is average price at the minemouth

Electricity is average price per kilowatt-hour consumed

FIGURE 8B: U.S. SIMULATION RESULTS (B/J AND FEA MODELS)
 QUADRILLIONS OF BTU's INDUSTRIAL SECTOR

	TOTAL	GAS	OIL	ELECTRICITY	COAL
1972 Actual (FEA Model)	23.0	10.6	5.7	2.5	4.3
Actual (B/J Model)	19.7	11.8	2.1	2.2	3.5
1975 CASE I (B/J Model)	18.6	11.8	2.0	2.5	2.3
CASE II (B/J Model)	18.7	11.7	2.1	2.5	2.3
CASE III (B/J Model)	19.1	11.6	2.3	2.5	2.6
1980 CASE I (FEA Model)	26.0	10.1	6.6	3.3	5.9
CASE I (B/J Model)	20.0	13.0	1.4	3.4	2.3
CASE II (FEA Model)	27.4	9.8	7.8	3.7	6.0
CASE II (B/J Model)	20.3	12.7	2.0	3.3	2.3
CASE III (B/J Model)	20.4	11.4	2.9	3.4	2.7
1985 CASE I (FEA Model)	28.7	10.5	7.4	4.1	6.7
CASE I (B/J Model)	22.3	14.1	1.1	4.4	2.7
CASE II (FEA Model)	30.6	9.7	9.3	4.6	6.9
CASE II (B/J Model)	22.6	13.7	2.0	4.2	2.6
CASE III (B/J Model)	22.2	11.3	3.4	4.5	3.1

CASE I = \$11/Bbl.

CASE II = \$7/Bbl.

CASE III = No O.P.E.C.

FIGURE 8C : MAJOR DIVERGENCES BETWEEN B/J AND F.E.A. SIMULATIONS

1. B/J projected gas consumption increases by about 20% from 1972 to 1985 for the price scenarios used, but the F.E.A. gas consumption projections decrease for the same price scenarios.
2. B/J projected oil consumption decreases by 1985 to about 50% of 1972 for \$11 per barrel oil and remains essentially constant for \$7 per barrel oil, but the F.E.A. projects a 30% increase for \$11 per barrel and a 60% increase for \$7 per barrel oil. (The major reason for this is the B/J exclusion of feedstocks.)
3. B/J projected coal consumption decreased by about 25% by 1985 for the price scenarios used, while the F.E.A. projects a 50-60% increase in coal consumption by 1985. In addition, as the oil consumption increases, while B/J model demonstrates the opposite trend in behavior.
4. Where, by 1985, the F.E.A. model results in 25% and 33% increases in total industrial energy consumption for the \$11 and \$7 per barrel cases, respectively, the B/J model results in 13% and 15% increases. (Again, part of the difference is due to feedstocks.)

FIGURE 8D : REASONS FOR GAS AND COAL DIVERGENCIES

1. The F.E.A. model has an own-price elasticity for natural gas of -1.5 vs. an estimated value of -0.8 in B/J model.
2. The F.E.A. model has an own-price elasticity for coal of -0.59 vs. an estimated value of -1.1 in the B/J model.
3. The F.E.A. model exhibits a negative cross-elasticity between coal consumption and oil prices.

Source for Figures 8A - 8D : Baughman and Zerhoot (11)

E) SUMMARY AND STATEMENT OF FURTHER RESEARCH

It will be recalled that the intent of this model review has been to assess the ability of each of the models firstly to specify and analyze the behavioral characteristics of long-run and short-run demand and secondly to provide a framework for examining the competitiveness of new technologies, particularly solar photovoltaics. The behavioral components of short-run and long-run demand were found to include three decisions:

- The consumer decision of whether to buy a fuel-burning consumer durable, capable of providing a particular consumer service (e.g. cooking, heating, lighting, air conditioning, etc.).
- The consumer decision about the characteristics fo the equipment purchased, technical characteristics and whether the equipment embodies a new technology.
- Given consumer equipment the consumer decision about the frequency and intensity of use.

All of the models treated these components of demand and new technologies with varying degrees of success. However even the best of the models require some improvement.

This Section first summarizes the model review. Based upon the summary and the actual review, the most important deficiencies in the current generation of energy demand models are identified. Sections E1 and E2 propose a model of residential energy demand that attempts to incorporate the strengths and avoid or improve upon the weaknesses in the models. Finally Section E3 presents an overview of ongoing efforts to accomplish the proposed model reformulation.

SUMMARY

Sections C and D reviewed but a portion of the energy demand models that have appeared over the past ten years. The discussion in those sections has

principally focused upon econometric or econometric/process/engineering models. The modelling efforts were divided into two groups: 1) models dealing with overall energy demand and interfuel substitution and 2) models dealing with the demand for a single fuel. The models reviewed in each category are repeated in Figure 9. The lists are by no means exhaustive; they hopefully span model space, forming a useful basis for suggestions for further research.

The B/J and FEA/PIES models represent generally the state of the art in overall energy demand modelling. By state of the art, I mean that they have, for the most part, utilized current theoretical and empirical techniques to model the demand for all energy forms on the part of the residential, commercial and industrial sectors, stressing interfuel substitution and explicitly approximating the differences between the long-run and short-run with a partial adjustment formulation. However while being state of the art these models exhibit a number of weaknesses. The strengths and weaknesses have been discussed in Section D.

An apparent reason for the methodological shortcomings in the FEA and B/J models is that in attempting to deal with the overall energy system, they have sacrificed important details. The models lack, for example, the richness of policy variables the extent of technological specificity and the multi-equation behavioral specification found in the interfuel substitution model of OR/H. However the OR/H modelling efforts deal only with the residential sector. Furthermore, the OR/H effort still relies on traditional logit analyses of consumer choice; as a result, while providing the best tool for residential energy demand analysis available, greater effort on modelling consumer choice and new technologies is required.

The B/J and FEA/PIES models also have less detail than many of the single fuel demand models, for example the Anderson (3) and Halvorsen (41) models. However, these works deal only with equilibrium electricity demand, ignoring inter-

FIGURE 9: MODELS REVIEWED IN SECTIONS C AND D

INTERFUEL SUBSTITUTION MODELS

Baughman/Joskow (BJ)
Federal Energy Administration
Project Independence Evaluation
System (FEA/PIES)
Oak Ridge/Hirst, et al. (OR/H)
Anderson
Erickson, Spann and Ciliano
(ESC)

SINGLE FUEL MODELS

Acton, Mitchell and Mowill
(1976), (AMM)
Anderson (1972), (1973)
Balestra (1967)
Cargill and Meyer (1971), (CM)
Fisher and Kaysen (1962), (FK)
Griffin (1974)
Halvorsen (1973)
Houthakker (1951)
Houthakker, Verleger, Sheehan
(1974), (HVS)
Mount, Chapman and Tyrrell
(1973), (MCT)
Mount and Chapman (1974), (MC)
Taylor, Blattenberger, Verleger/
DRI (1977), (TBV)
Willis (1977)
Wilson (1971)

fuel substitution and the differences between the long-run and short-run. The partial adjustment residential models of Mount, Chapman and Tyrrell [MCT, (68)] and Houthakker, Verleger, Sheehan [HVS, (56)] also focus upon electricity demand alone.¹ While these single fuel models provide more detail than the B/J and FEA/PIES models for electricity demand, they ignore gas and oil demands. These single fuel models provide greater disaggregation than B/J and FEA/PIES by analyzing the residential sector alone. Furthermore, Mount, Chapman and Tyrrell [MCT, (68)] also explicitly disaggregate and analyze the commercial sector demand for electricity along similar analytic lines applied to the residential sector. The MCT (68) industrial model and particularly the Anderson industrial model show greater analytic sophistication than B/J and FEA/PIES; however, these efforts again concentrate only upon electricity demand. The Taylor, Blattenberger, Verleger/DRI (TBV); Acton, Mitchell and Mowill (AMM); and Fisher and Kaysen (FK) analyses of the residential demand for electricity introduce the short-run constraints embodied in the stock of residential energy-consuming equipment. TBV and AMM utilize a theoretically more sound multi-part tariff formulation rather than the usual typical electric bill or average electricity price.

While the B/J and FEA/PIES efforts reflect state of the art in overall energy models and in spite of the fact that single fuel demand analyses provide greater analytic refinement, extended efforts are still required to properly differentiate and delineate the short-run and long-run characteristics of demand and to properly evaluate the potential of new technologies. The entire generation of energy demand models that B/J, FEA/PIES and other efforts reflect have reached a stage of forced obsolescence. New work done on choice modelling (generalized logit [Hartman (43)] and covariance probit [Hausman and Wise (47)]), production/cost duality [Econo-

¹Many of these models are compared in greater detail in Charles River Associates (25).

metric International (33)], and the explicit differences between short-run and long-run energy demand [DRI (29); AMM (1)] provides extremely cogent arguments for completely respecifying the FEA and B/J demand modules and most other analyses of energy demand.

The extended modelling suggested in the following two sub-sections will attempt to provide the following improvements (repeated here from the Introduction):

- Explicit dichotomization of the behavioral characteristics and policy variables for short-run and long-run demand.

In the short-run, the characteristics and use of the energy-burning capital stock are fixed. Behavioral specifications and policy variables must take into account that demand responses can only take the form of conservation and altered capital utilization. In the long-run, the size and characteristics of the capital stock are variable; thus in the long-run, the characteristics of new technologies and interfuel substitution (through changes in the capital mix) become relevant. Likewise, appliance efficiency taxes and standards, and appliance capital costs become relevant policy variables in addition to the standard operating costs of the fuels.

- Utilization of appropriate models and data for consumer choice.

Conditional logit has been utilized extensively for the analysis of inter-fuel substitution in a partial adjustment framework. However, conditional logit as used in the literature suffers from a number of difficulties including: the imposition of constant cross-elasticities [see Baughman and Joskow (9); (12), (13), Domencich and McFadden (32), Hartman (43), Hartman and Hollyer (45)]; implied misspecification [Hartman and Hollyer (45) and Hartman (43)]; excluded variables; and the restrictive underlying model of individual choice [Hartman (43) and Hartman and Hollyer (45)]. Such modelling of consumer choice should

utilize generalized logit formulations [Hartman (43)] or covariance probit formulations [Hausman and Wise (47)]. Furthermore the choice methodologies should be applied to changes in the appliance stock rather than the actual stock [see Hartman and Hollyer (45)].

- Appropriate treatment of new technologies.

While generalized logit and covariance probit avoid some of the difficulties inherent in conditional logit, the treatment of new technologies is not trivial for either new alternative and careful formulation is required.

The modelling research proposed here is currently being pursued under contract to the Department of Energy.

1) OVERVIEW OF THE PROPOSED MODEL REFORMULATION

Figure 10 provides an overview of the proposed model. In 10A, short-run demand (d_i) is explicitly modeled for the fuels (i) = electricity (e), gas (g), oil (o) and coal (c). Short-run demand for fuel i (d_i) is made a function of own-price and cross-prices of fuels (P_j); the efficiencies of the stock of fuel-burning equipment (EFF_j); the size of the fixed stocks of the fuel-burning equipment (K_j); income (y); climatic variables ($TEMP$, including heating and cooling degree days); demographic factors (DEM , including a regional dummy and percentage of families in single family homes); and other exogenous variables (X_{i1}). For data reasons, the short-run is assumed to be a year; hence, the fuel-burning equipment stocks (K_j) and their characteristics (EFF_j) are considered fixed. This is not a particularly severe assumption for the more important uses of fuels. The short-run formulation will be discussed more fully below, as well as the specific fuel uses to be analyzed.

This proposed treatment of short-run demand for individual fuels is, in general, similar to that of FK, AMM, TBV and Wills in that appliance stocks are taken as given and demand is a capacity utilization issue. These single fuel models

FIGURE 10: OVERVIEW OF RESIDENTIAL DEMAND MODEL

A) SHORT-RUN DEMAND:

$$d_i = F_i(P_j, EFF_j, K_j, y, TEMP, DEM, X_{i1}) ; i, j = e, g, o, c$$

B) LONG-RUN DEMAND:

$$\bullet S_i = G_i(P_i, EFF_i, CAP_i, X_{i2}) \quad i = e, g, o, c$$

$$\bullet \Delta K_{it} = \Delta K_t \cdot S_i \quad (\text{must predict } \Delta K)$$

$$\bullet K_{it+1} = K_{it}(1 - \delta_i) + \Delta K_{it}$$

Share equations utilizing Logit or Probit

C) TREATMENT OF NEW TECHNOLOGIES--DETERMINATION OF CAP_i, EFF_i:

• Exogenously; then into share equations

• Endogenously

a) Specify discount rate and efficiency/capital cost tradeoff, yielding EFF_i and CAP_i

b) Capital efficiency supply and demand model:

$$D: CAP_i = D_i(EFF_i, EFF_j, P_i, P_j, y, X_3)$$

$$S: CAP_i = S_i(EFF_i)$$

are the best of the reviewed group in meeting model evaluation criteria ii) and iv): proper identification and incorporation into variables in the model of policy issues and technological considerations for the major market participants; and utilization of the appropriate behavioral models and underlying behavioral assumptions. The demand formulation here is intended to incorporate the insights and variables of those analyses and extended the effort to include characterization of the efficiency of the appliance stock (EFF_j). Much effort has been expended for six fuel uses, as discussed in Section E2.

Figure 10B indicates the form of the long-run analysis. In the long-run, the stock and characteristics of the residential fuel-burning equipment will be variable. The first long-run equation states that the shares (S_i) and penetration of traditional and new fuels and technologies in the market for new residential appliances will depend upon the fuel operating (P_i) and capital (CAP_i) costs of the alternative equipment for each fuel (i), the technical characteristics of that equipment (EFF_i) and other technical and socioeconomic factors characterizing the technology and/or the persons making the choice. The share equation relates to changes in the fuel-burning appliance stock (ΔK); hence consumer durable expenditures for various appliances must be modeled also. Once the shares of changes in the appliance stock for fuel i and the retirement rate (δ_i) are known, the stock of fuel-burning equipment for each fuel will be given for the following year by $K_{i\ t+i} = K_{i\ t}(1-\delta_i) + \Delta K_{i\ t}$ (third equation in 10B). The form of the share equations, the levels of disaggregation of fuel uses and appliance stocks and the methodological details are discussed more fully below.

Figures 10A and 10B indicate the explicit separate analytic treatment of the short-run and the long-run. The discussions of Sections C and D emphasized the need for such separate treatment. The models that dealt best with demand behavior and variables of those analyses and extend the effort to include characterization of the size and the efficiency of the appliance stock (EFF_j). Much effort has been expended for six fuel uses, as discussed in Section E2.

(e.g. FK, AMM, TBV, OR/H) utilize such a multi-equation approach. Furthermore it should be noticed that the treatment in Figure 10 permits richer analysis of technological characteristics in terms of capital costs and equipment efficiencies. Furthermore the long-run demand analysis will be designed to deal explicitly with new technologies as indicated in Figure 10C. Two techniques are available for treating new technologies: 1) exogenous specification of the characteristics of the new technologies facing consumers including capital cost (CAP_i) and efficiency (EFF_i) and inclusion into share equations, and 2) endogenous determination of CAP_i and EFF_i . Two techniques are available for the endogenous determination of CAP_i and EFF_i : firstly, analysis of the efficiency/capital cost tradeoff and specification of a discount rate; and secondly a more formal supply and demand model for capital stock efficiency. These alternative treatments of new technologies are examined more fully below.

2) MORE DETAILED SPECIFICATION OF PROPOSED MODEL REFORMULATION

The residential energy demand model formulation in Figure 10 was described at a general level. More specificity is required. Figure 11A indicates the specific fuel categories and fuel uses that are being examined in the model. The tentative fuel categories include the usual gas, oil and electricity in addition to coal. Coal has been included for policy assessment reasons due to its potential exploitation in the future. The tentative fuel uses (i.e. appliance type) include space and water heating, cooking, air conditioning, clothes drying, refrigeration/freezing and other uses. Interfuel substitution is possible in space heating, water heating, cooking, clothes drying, and central air conditioning. The remaining categories are essentially electrical.

Figure 11B repeats the short-run demand specification found in Figure 10A. Figure 11B suggests a potential theoretical specification and coincident potential forms of indirect utility to be tested. The potential forms for indirect utility are

FIGURE 11A: ANALYTIC DISAGGREGATIONS

TENTATIVE FUEL CATEGORIES

GAS

OIL

ELECTRICITY

COAL

OTHER/NONE

TENTATIVE FUEL USES

SPACE HEATING

WATER HEATING

COOKING

AIR CONDITIONING

CLOTHES DRYING

REFRIGERATION/FREEZING

OTHER

FIGURE 11B: SHORT-RUN DEMAND (EQUIPMENT STOCKS FIXED)

$$d_i = F_i(P_j, EFF_j, K_j, y, TEMP, DEM, X_{i1})$$

$$i, j = e, o, g, c$$

POTENTIAL THEORETICAL SPECIFICATION:

INDIRECT UTILITY FORMULATION FALLING OUT OF CONSUMPTION/EXPENDITURE DUALITY; DERIVATION OF MARSHALLIAN DEMAND.

POTENTIAL FORMS OF INDIRECT UTILITY TO BE TESTED:

- GENERALIZED QUADRATIC MEAN OF ORDER p:

$$V(W_i) = \sum_{i=1}^n \alpha_i W_i + \left(\sum_{i=1}^n \sum_{j=1}^n \beta_{ij} W_i^{p/2} W_j^{p/2} \right)^{1/p}$$

- GENERALIZED LINEAR:

$$V(W_i) = \sum_{i=0}^n \sum_{j=0}^n \beta_{ij} W_i^{1/2} W_j^{1/2}$$

- C.E.S.:

$$V(W_i) = \sum_{i=0}^n \alpha_i W_i + \left(\sum_{i=0}^n \beta_{ii} W_i^p \right)^{1/p}$$

- COBB-DOUGLAS:

$$V(W_i) = b \prod_{i=0}^n W_i^{\beta_i}$$

- TRANSLOG:

$$V(W_i) = \sum_{i=1}^n \beta_i \ln W_i + 1/2 \sum_{i=1}^n \sum_{j=1}^n \gamma_{ij} \ln W_i \ln W_j$$

Where W_i are the terms found in F_i above.

stated generally in Figure 11B and the explicit imposition of such constraints as quasi-convexity and non-increasing monotonicity in prices are not explored here. At present it is not clear that the indirect utility approach will be utilized or more straight-forward short-run specifications such as those found in TBV, AMM, and FK.

The short-run demand will be estimated for the fuel types found in Table 11A. Consumption data is not disaggregated finely enough to permit demand modelling for both fuel type and end use. Short-run demand is made a function of fuel prices (P_j), appliance stocks (K_j), appliance efficiencies (EFF_j) and the remaining socioeconomic and demographic variables (y , TEMP, DEM, and X_{i1}) defined in Figure 10A. The appliance stocks and their average efficiencies can be disaggregated to the six fuel uses found in Figure 11A. The essence of short-run demand assumes the constancy of K_j and EFF_j . As a result it is possible that d_i should be a function of only P_i , K_i and EFF_i rather than P_j , K_j and EFF_j , $j = e, o, g, c$. However even in the short-run there may be some interfuel substitution. Therefore we intend to assess own- and cross-elasticities of d_i with respect to P_j , $j = e, o, g, c$ given EFF_j and K_j . Again this formulation expands upon the efforts of FK, AMM, TBV and Wills.

Short-run demand has been fairly well specified and analyzed by some of the single fuel energy models discussed in Section C. However, the analysis of the long-run is inadequate in all the single fuel and interfuel substitution models reviewed. In the long-run, the penetration of new technologies is important. Adequate treatment of demand for new technologies and traditional technologies in changes in the appliance stock is required.

Table 11C indicates the long-run approach in more detail. The share equation for changes in the appliance stock is given in the Figure for fuel $i = \text{oil}$ (o) and it is a function of alternative fuel prices, capital costs, equipment efficiencies and other technological, personal and socioeconomic factors. The

FIGURE 11C: LONG-RUN DEMAND ANALYSIS
(CHANGES IN THE FUEL-BURNING EQUIPMENT STOCK)

SHARE EQUATIONS: (Let $i = 0$)

$$S_o = G_o(P_e, P_o, P_g, P_c, EFF_e, EFF_o, EFF_g, EFF_c, CAP_e, CAP_o, CAP_g, CAP_c,$$

plus other technological, personal and socioeconomic factors)

POTENTIAL SHARE EQUATION SPECIFICATION

- Conditional Logit
- Generalized Logit
- Probit

INCLUSION OF NEW TECHNOLOGIES

- New bundles of characteristics in separate share equations
- Maintenance of traditional fuel disaggregation (Gas, Oil, Electricity, and Other) and endogenous treatment of new technologies within each traditional fuel category

exact form of G_0 will depend upon whether conditional logit, generalized logit or probit analysis is utilized. Each of the three techniques has its own strengths and weaknesses.

The use of share equations was found in the OR/H, B/J, FEA/PIES and Anderson interfuel substitution models and in the FK appliance demand analysis. These models however utilized regression forms of conditional logit or variations of it. They did not examine the use of probability models utilizing generalized logit or covariance probit.

The long-run modelling effort here will assess alternative specifications including regression forms of conditional logit and likelihood forms of conditional logit, generalized logit and covariance probit.

Examples of all these techniques exist in the literature. Probability models and models of individual choice have become extremely popular in the recent past, particularly in the analysis of choices among alternative energy sources. The models of individual choice have focused upon micro decisions of individuals among discrete alternatives (see 43 and 47). More generally, probability models have been applied to aggregate data and are assumed to reflect the aggregation of individual decisions among discrete alternatives (3,4,5,9,10,12,13,43,45,49,58). While notions of individual choice form the basis for the more aggregated probability models, alternative techniques are utilized in estimation -- maximum likelihood estimates are obtained for the individual choice models, while regression techniques are utilized for the aggregated data (where replication is assumed).

Probability models of individual choice consist of two components: a formulation of random utility and the stochastic specification of that utility (see 43,47). Usually separable direct random utility is assumed. With Weibull error terms, logit analysis results. With normal error terms, probit analysis results. For the probability models of individual choice, logit and probit analyses are

utilized most frequently. In the case of binary choice, the probit and logit formulations yield essentially the same results in most applications to date¹. In the multi-choice extension, logit analysis has been used most frequently because of the ease of computation. The use of probit analysis for n choices ($n > 2$) is computationally difficult because in order to obtain likelihood estimates, evaluation of $n - 1$ multivariate normal distributions is required. While several authors (47) claim that current computer software makes the analysis of up to five alternatives possible, probit analysis still requires substantially more computational effort than logit analysis.

In light of such computational burdens, it might seem curious that probit would be used at all. One reason, of course, is the much discussed logit assumption of the "independence of irrelevant alternatives."² This assumption need not be a drawback. For example, in the case of evaluating a new alternative when that new alternative is sufficiently different in attribute space from all existing alternatives, the underlying assumptions of logit analysis seem reasonable and the ease with which the new alternative is built into the model is desirable. However, when a new alternative is very similar to an existing alternative, the implied consequences of the logit model are unacceptable.³ Furthermore, the use of logit formulation in conjunction with the usual treatment of random utility as separable generates misspecification problems (see 43).

Some of the difficulties that arise in using logit analysis (which are invariably linked to the "independence of irrelevant alternatives") are due to the

¹The reason is that most uses of probit have assumed the independence of alternative choices. See Hausman and Wise (47).

²As Hausman and Wise point out, it would be more descriptive to label this properly the "independence of relevant alternatives." (47, pp. 3).

³The red bus/blue bus problem. See (47).

specific utility formulation utilized in the analysis of discrete choice, in addition to the assumption about the form of the distribution of the error terms. A more general specification of utility will avoid the difficulties of the more restrictive formulation and also permit statistical tests of the validity of that same restrictive specification (see 43). By avoiding the difficulties confronted in the traditional application of logit analysis, the more general logit formulation may permit continued use of logit in many simulation contexts, thereby avoiding the more onerous computational burdens of using the more theoretical elegant probit analysis.

The long-run analysis indicated in Figure 11C will attempt to identify the best treatment of the characteristics of long-run demand from these alternative techniques. However conditional logit, generalized logit and covariance probit all have difficulties in dealing with new energy technologies. Thus the introduction of new technologies must be performed as a separate topic.

As stated in Figure 11C, new technologies can be introduced in two ways: by including the new technologies as a new bundle of characteristics in separate share equations (whether conditional logit, generalized logit or covariance probit is used) or by maintenance of traditional fuel disaggregations and the endogenous treatment of new technologies within each traditional fuel category. The latter method will be discussed below with Figure 11D. The treatment of new technologies as bundles of characteristics in separate share equations is the usual approach utilized with conditional logit (see Domencich and McFadden,(32). This approach suffers from the "independence of irrelevant alternatives" [see Hartman (43), Hausman and Wise (47)]. The inclusion of new technologies into a generalized logit or covariance probit formulation requires the arbitrary estimation of particular parameters without actual data [see Hartman (43, 47)]. As a result all three techniques face difficulties in handling new technologies.

In order to avoid the problems of assessing new technologies through separate

share equations, Figure 11D indicates the treatment of new technologies within traditional fuel categories. It should be thought of as heuristic; the formal details of the approach are to be worked out in the more detailed analysis proposed. The figure represents the technological trade-off for alternative technologies of first cost (appliance cost or cost of capital services) and operating cost. The technologies A through F are assumed to dominate all others. For exposition sake, assume point A indicates the capital cost/operating cost tradeoff for a traditional gas furnace with typical duct-work and room register systems. Point B represents the increased capital cost and decreased operating cost (lower energy use) that characterize a gas heat pump. The points between A and B reflect traditional gas heat with varying degrees of duct-work, insulation and increased burner efficiency which raise capital costs but lower operating costs through increased efficiency. Likewise points C, D, E and F are meant to reflect the capital cost/operating cost characteristics of gas heat in combination with some variation of solar heat. Notice that this formulation permits the inclusion of a large (infinite) number of "new technologies" where the new technology can consist of combinations of solar and traditional fuel back-up device and where the combinations can vary from 0 to 100%.

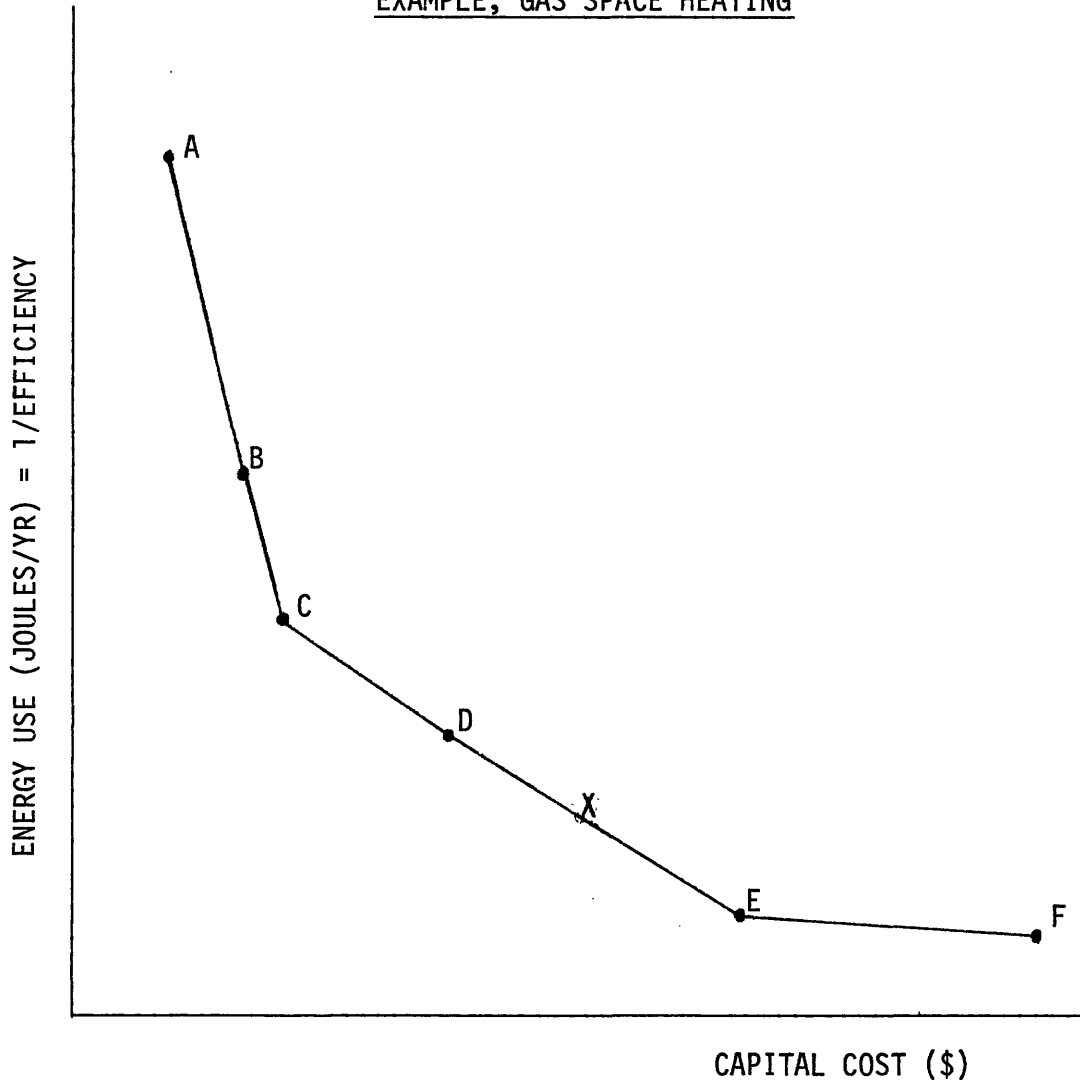
The trade-off reflects the fact that increased capital cost will purchase increased equipment efficiency, hence lowered annual operating costs. Given this technological trade-off, specification of a discount rate (or pay-off period to the management scientists) will determine the intertemporal cost trade-off in point X. Point X assimilates information on all new technologies affecting gas use and intertemporal consumer preferences to determine the capital costs (CAP_g), and equipment efficiency (EFF_g) demanded for gas space heating in this example. Given the determination of the intertemporal characteristics of the demand for gas-fixed appliances (i.e. CAP_g and EFF_g), these capital costs and technological

FIGURE 11D:

ENDOGENOUS TREATMENT OF NEW TECHNOLOGIES

WITHIN TRADITIONAL FUEL CATEGORIES

EXAMPLE, GAS SPACE HEATING



* Points A - F reflect trade-off between operating cost and capital cost for alternative technologies; for example

- A) traditional gas heating
- B) gas heating with heat pump
- C) gas heat with solar thermal
- D) gas heat with solar photovoltaic

* Specification of discount rate determines point x

* Point x determines CAP_g and EFF_g for space heating for share equations

characteristics (efficiencies) can be introduced into the share equations (whether logit or probit) for the traditional fuels to combine with other fuel and personal characteristics (operating costs, income etc.) to fully assess fuel/technology penetration and consumer choice.

This approach overcomes some of the difficulties inherent in the usual exogenous treatment of new technologies through new share equations. It avoids the "independence of irrelevant alternatives" (in conditional logit). It avoids the difficulty of arbitrarily assigning values to particular likelihood estimates in the choice model [for generalized logit (see 43) and covariance probit (see 47)]. It avoids the problem of requiring a large number of additional share equations when the number of new technologies is large (in conditional logit, generalized logit and covariance probit). This is particularly important in the modelling of residential fuel demand and the penetration of new technologies, as seen in Figure 11D. The curve in 11D reflects a continuous trade-off of capital and operating costs as varying degrees of insulation and new technologies are assumed. As discussed above, solar photovoltaics (PV) will be used in combination with traditional fuel back-up devices in combinations of 0-100% of energy load; hence, the capital cost/operating cost trade-off characterizing the PV/gas installation will include an infinite variety of potential forms of the new technology. The trade-off curve in 11D and the use of the intertemporal utility maximization permits analysis of a richly specified array of new technologies. The inclusion of these technologies into separate share equations would be impossible.

However the treatment in 11D still has its own difficulties. Firstly the trade-off between current and future costs takes place only within each traditional fuel category. Clearly, this is inappropriate. A consumer optimizing operating cost savings over time would examine the savings from new technologies in all fuel categories. Secondly, this technique dichotomizes consumer behavior

into intertemporal utility maximization (Figure 11D) and current utility maximization (inclusion of CAP_g and EFF_g) into current period share equations based upon current utility maximization.

In order to incorporate intertemporal interfuel comparison, the analysis of new technologies requires modelling demand for a given technology (as measured by its efficiency) while also assessing cross-elasticities for other fuels/technologies (through their efficiencies). Figure 11E summarizes such a supply and demand model. The supply of efficiency is merely the mirror image of the technological trade-off curve found in Figure 11D. It incorporates the dominant technologies' ability to provide increasing efficiency at increasing capital costs. The demand curve reflects the capital cost consumers are willing to pay for equipment of fuel type i , given EFF_i , EFF_j ($j \neq i$), the alternative fuel operating costs P_i and P_j ($j \neq i$), income and other exogenous variables.

3) OVERVIEW OF ONGOING RESEARCH EFFORTS¹

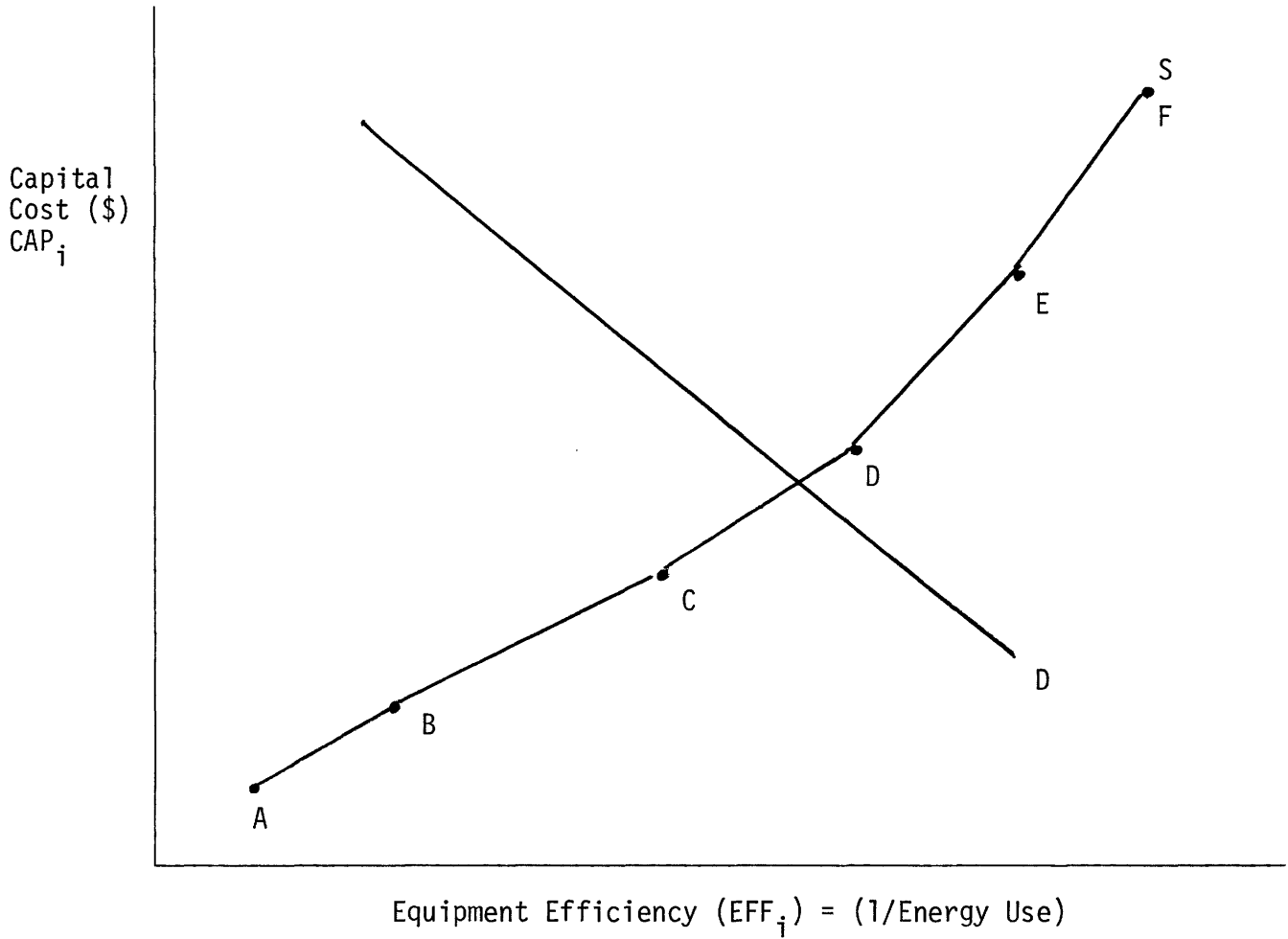
In order to accomplish the residential energy demand model reformulation outlined in Sections E2 and E3, research is currently being pursued in three major areas: data acquisition, extension and refinement; short-run energy demand modelling; and long-run energy demand modelling. The results of this research will be a documented data base for future residential energy demand analysis and a series of discussion papers summarizing the specifications and empirical results developed for components of the reformulated model. I briefly summarize the efforts in these three areas.

● DATA ACQUISITION, EXTENSION AND REFINEMENT

To facilitate estimation and hypothesis testing for theoretical analysis in short-run and long-run energy demand, a data base has been accumulated. The data

¹Research being conducted for Department of Energy by the MIT Energy Lab.

FIGURE 11E: CAPITAL EFFICIENCY SUPPLY AND DEMAND MODEL



Demand: $CAP_i = D_i(EFF_i, EFF_j, P_i, P_j, y, X_3)$

SUPPLY: $CAP_i = S_i(EFF_i)$

base incorporates the best data available for energy prices, appliance stocks, appliance shipments (by end-use in Figure 11A), energy demand and socioeconomic/demographic variables for a time-series (1959-1977) of state cross-sections. The principal sources have been (10) and (30). This data has been supplemented with some primary data gathering for some data series (for example oil consumption and gas availability) and an extensive primary data gathering effort attempting to characterize fuel-burning appliance efficiency, quality and capital cost for appliances characterized by fuel and fuel use (see Figure 11A). This data is being developed for the same pooled time-series/cross-section. It will play an important role in both the short-run and long-run demand analyses.

● SHORT-RUN DEMAND ANALYSIS

The short-run demand research has proceeded by specifying demand equations of the form in Figure 11B. The essence of the short-run demand is fixity of appliance stock and appliance characteristics; hence the research has specified demand formulations that have fixed the appliance stock and its efficiency for each of the fuels and fuel uses in Figure 11A. The variables that vary in the short-run are fuel prices, income, climatic variables etc.

Given the data available, the short-run demand equations are specified for the four fuels in Figure 11A. As a result appliances must be aggregated across fuel uses. In the models reviewed, FK, AMM, TBV and Wills dealt with appliance aggregation in different ways. The short-run analysis will examine alternative methods of aggregating appliance by fuel. Other issues that will be addressed include: potential simultaneity biases/inconsistencies given the presence of fuel supply curves; the effects of downward sloping multi-part tariffs for gas and electricity; and regional homogeneity in demand.

● LONG-RUN DEMAND ANALYSIS

The long-run demand research is focusing upon both the formal specification

of consumer utility and the stochastic specification in choice models applied to the fuels in Figure 11A for each of the fuel uses in that Figure. Examination of the theoretical and stochastic appropriateness of alternative utility specifications using logit and probit are being conducted. Where possible, hypothesis testing is being conducted to reject particular utility formulations.

The comparative assessment of logit and probit includes their ability to handle the new technologies.

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