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FRONTIERS IN ENERGY DEMAND MODELING

by

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CONTENTS

	Page
Introduction and Summary	1
A) Delineation of an Energy System and an Energy System Model	4
B) Energy Demand and its Treatment in the Literature	
I) Overview of Demand and Demand Models	7
II) Critique of the Models	14
III) Research in Progress -- Advanced Multi-Equation Models Currently Being Used or Developed	32
C) Summary and Formalization of Frontier Energy Demand Model Characteristics	35
References	43

INTRODUCTION AND SUMMARY

The process of model review is necessary and important.[1] It is important principally because it helps inform market valuations of the stock of available policy models and it suggests directions for future model development. To borrow the terminologies of capital theory and the theory of technological change, a body of policy models constitutes a capital stock of varying vintages, efficiencies and stages of obsolescence. As new modeling techniques, paradigms and data bases are developed and exploited, they are added to the stock of models. The attendant stages of invention/innovation, exploitation and diffusion of modeling techniques are genealogically quite similar to those of an emerging technology. In the face of such capital accretion, model review permits a reflection upon the directions and value of past modeling development, its neutral or non-neutral biases and the desirable induced direction of future model development.

The major purposes of this paper reflect such motives. The paper first introduces and critiques an array of models that constitute the capital stock of energy demand models and second explores particularly promising directions to which current and future energy demand modeling is being and should be induced. As a result, the paper attempts to do

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[1] The activity of critically reviewing a group of positive or normative models for 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 modelers whose models are being reviewed. In the second place, the review function perforce limits the group 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 such potential difficulties, the process is important.

more than the traditional model review.[1] After identifying and critically evaluating the models that treat energy demand, the paper attempts to build upon the rich history of such efforts by making some detailed suggestions for advancing the frontiers of energy demand modeling.

The paper focuses upon only one component of a complete energy system model - the demand component. In particular, I focus upon energy demand models for the residential, commercial and industrial sectors in both static and dynamic terms. However, it is useful to present some perspective regarding the relationship of energy demand to the entire energy system. Section A attempts to provide such perspective. The Section explores a full energy system model and indicates it is composed of a static set of models of demand, supply, and market clearing forces in addition to a set of dynamic models tracing the time pattern of forces effecting changes in demand and supply. The position of demand in the energy system is highlighted in Section A.

Given this perspective, Section B examines energy demand itself more closely and discusses in detail the behavioral decisions involved. If one is purporting to model energy demand, the model must accurately reflect these decisions and the technological facts being studied. Section B indicates how an energy demand model can analyze the relevant decisions and furthermore introduces and reviews a number of models that do such analysis.

It will be found (in greater detail) in Section B that the history of this literature has evidenced, in general, an increasing sophistication in the behavioral specifications representing the demand decisions,

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[1] See, for example, Hoffman and Wood (1) and Taylor (2).

in addition to the econometric techniques and data utilized. Many early attempts in residential, commercial and/or industrial demand modeling were aggregate, single equation, long-run equilibrium demand models focusing on a single fuel. Such models, in general, utilized only fuel price as a decision variable; they paid little attention to the characteristics of fuel-burning equipment and the differences between long-run and short-run demand. In the face of a growing awareness of the inadequacies of these models, the equilibrium models gave way first to more dynamic partial-adjustment demand models for a single fuel and then to partial-adjustment interfuel and interfactor substitution models for residential, commercial and industrial energy demand. The interfuel substitution models explicitly analyze competition among all fuels. However, even the more dynamic partial-adjustment interfuel and interfactor substitution models have required improvement. Explicit multi-equation behavioral specifications are required. Section B closes by examining several multi-equation models.

While Section B identifies the decisions involved in energy demand and reviews the treatment of those decisions by several models, it is left to Section C to summarize what I feel to be the important characteristics of and issues examined by frontier energy demand modeling efforts. While these characteristics will be explored in some detail in that Section, they can be summarized as follows:

- Explicit Analytic Treatment of both Long-run and Short-run Demand, with the purpose of identifying behavioral characteristics and policy variables specifically relevant to each.
- Appropriate Level of Disaggregation of energy end-use, with the purpose of permitting technological specificity in treating fuels and the fuel-burning capital stock.

- Appropriate Treatment of New Technologies.
- Utilization of Appropriate Models and Data for Residential Consumer Choice and for Dynamic Modeling of Industrial and Commercial Demand.

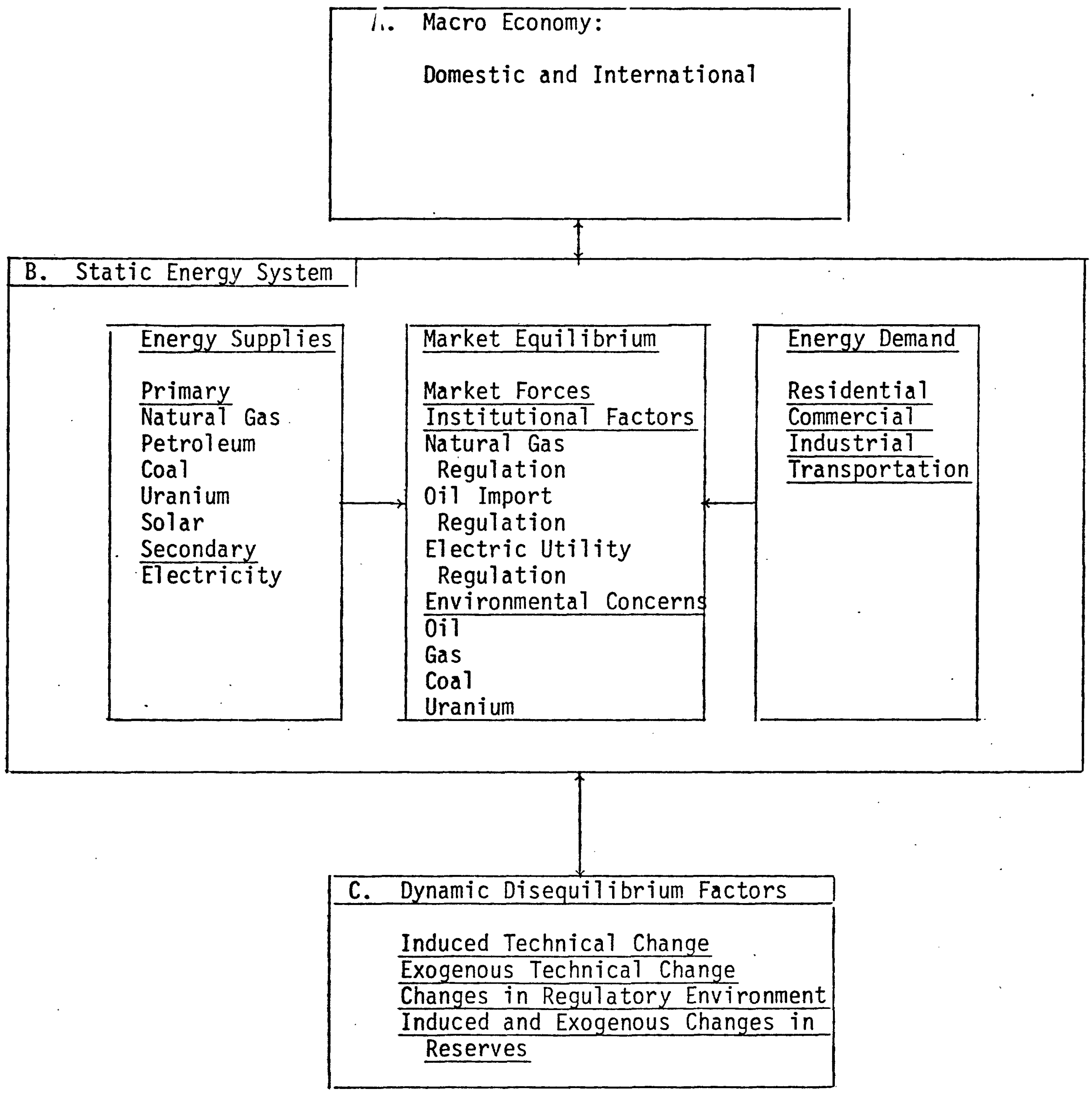
In addition to discussing these characteristics in greater detail, Section C introduces a paradigm model for residential, commercial, and industrial demand. The modeling discussion utilizes the notation of theoretical microeconomics.

A) Delineation of an Energy System and An Energy System Model

An energy system of a national economy is composed of a group(s) of suppliers of various energy forms and a group(s) of users or demanders of various energy forms, linked together by a set of markets, institutions and arrangements whereby users of energy forms can obtain desired energy forms from the suppliers. These suppliers, demanders and their market/institutional interconnections are furthermore embedded in the greater national and international economies. Thus, an energy system itself is inextricably interwoven with other markets for goods and services through sets of market/institutional interconnections.

While an energy system sounds complicated in the abstract, it is simpler in reality to give some coherence to the maze of various participants through an energy system model. A model of an energy system attempts to identify and formalize in economics, mathematics and statistics the behavior of the users and suppliers of various energy forms and the forces that bring demands and supplies into an equilibrium. An energy system model should provide an analytic framework for demands, supplies and their equilibrium at any point in time - given the state of the capital stock, knowledge, technology and known reserves. Furthermore, an energy system model should formalize the dynamic, long-run dis-

FIGURE 1: Components of A Static Energy System and its Relationship to the Macro Economy and Factors Generating Dynamic Disequilibrium



equilibrium behavior generated by changes in demands for and supplies of various energy forms in response to changes in the size and characteristics of the stocks of capital, knowledge, technology and known reserves. At a minimum the energy model should be able to deal with such dynamic disequilibria when they are introduced exogenously. At best, the energy system model could endogenously predict the existence and direction of such changes in the stocks of capital, knowledge, technology and known reserves. Finally, an energy system model should indicate how the energy system relates to the national and international economies in which it operates.

Figure 1 attempts to lend some structure to the discussion. At any point in time, given the state of the macro economy A) and technology, capital stocks and known reserves C), the static energy system B) and a model of it equilibrates supplies and demands for all energy forms. Clearly the more disaggregated the static energy system model, the better the policy tool for disaggregated policy measures (e.g., appliance efficiency taxes in the residential sector; use of cogeneration in the pulp and paper industry; sulfur tax on high sulfur coal). However, the more disaggregated the static model, the more complicated it becomes analytically and statistically and the more onerous are the data demands and computation costs. The static model in the Figure is fairly disaggregated; it is close to the level of disaggregation found in the FEAS/PIES model (3, 4). However, more disaggregation is conceivable, such as breaking out 2 digit SIC categories of industrial demand.

The causal directions of the arrows from A to B and C to B in Figure 1 run both ways. For the static energy system, the causal flow runs from the macro economy and the state of technology, capital and reserves. However, given the importance of the energy system to national economy, the static solutions do effect changes in the macro economy and the capital stock, technology, regulatory environment and known (available) reserves. The time sequencing of these mutual interactions would be modeled by a dynamic energy system model.

Needless to say, a full dynamic model of an energy system stressing its internal structure and its relation to the macro economy would be a formidable undertaking. Many efforts focus only upon supply (5-12); others (as discussed here) focus only on demand. Some focus upon the entire static model, conditional upon the macro economy and the state of technology, capital stock and known reserves.[1] Still others try to treat the macro economy and the energy system as mutually endogenous (16-18).

As mentioned above, I intend to focus upon static and dynamic models for the residential, commercial and industrial sectors. From Figure 1 it is clear that such a limitation leaves out considerable work in Transportation demand models (19-21). It also excludes the remainder of interactive components of Figure 1. In spite of these significant exclusions, it will still be difficult to review the important models of residential, commercial and industrial energy demand in existence or currently being developed.

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[1] Such an effort is currently being investigated (13-14) by L. Lau and D. Fromhalzer to combine the Oak Ridge/Hirst residential demand model, the Oak Ridge/Jackson commercial demand model, the Jack Faucett transportation model, the ISTUM (15) industrial demand model, the Hudson-Jorgensen model, and the Fossil 1 supply model (12). The models not referenced in this footnote are referenced above and in Section B.

B) ENERGY DEMAND AND ITS TREATMENT IN THE LITERATURE

I) Overview of Demand and Demand Models

Section A explored the general dimensions of a complete energy system model with particular emphasis placed upon demand. Before we are ready to discuss actual models of energy demand, it will be useful to look closely at the real world phenomena being modeled. To that end, this section (BI) first discusses the behavioral characteristics of energy demand in more detail and introduces the models of interest. Following this discussion the actual energy demand models are critiqued in BII. BIII finally closes the section be examining examples of more advanced energy demand models.

The demand for energy on the part of the residential and commercial sectors is a derived demand for the end-use services provided by that energy source in conjunction with the capital used with that energy source. For the industrial sector, this demand for energy and capital operates in conjunction with demand for other factors of production, such as labor and materials. Any analysis of energy demand should therefore deal with the fact that fuels and fuel burning applicances/equipment are combined in varying ways to produce a particular residential, commercial or industrial service: analysis of the demand for energy must treat in some fashion the interactive demands for both fuel burning capital and the fuel used by that capital stock.[1]

Let us try to summarize this energy demand behavior in general. Three types of decisions on the part of any energy user (demander) are involved:

1) The user decision of whether to buy or replace a fuel-burning durable good, capable of providing a particular residential/commercial/industrial comfort service (e.g., heating, lighting,

[1]The interactive character of these demands has evidenced both complementarity and substitutability. For some clarification of the issues involved with an industrial focus, see (22).

air conditioning, cooking, etc.) or industrial/commercial process service.

2) The user decision (choice) about the technical and economic characteristics of the equipment purchased and the type of fuel it uses, and whether the equipment embodies a new technology.

3) Given such equipment and its technical characteristics, the user decision about the frequency and intensity of use (capital utilization).

These three decisions span the short-run (when the capital stock and its characteristics are fixed) and the long-run (when the size and characteristics of the capital stock are variable).[1]

Upon reflection, the factors affecting these three decisions are readily identifiable for residential, commercial and industrial users. For the residential user, for example, the decision to buy a new residential appliance will depend upon his income, the climate in which he lives, the cost of purchasing (capital cost) and operating (fuel costs) the appliance, and general socioeconomic trends affecting the popularity of such appliances.[2] The decision about the type of appliance purchased and its requisite fuel will depend upon a comparison of the capital and

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[1]While it may be useful to think of the decisions as sequential, they are also clearly interactive. For example, the choice regarding fuel type and equipment characteristics (2) can affect the decision to hasten or postpone the durable purchase (1); thus, the presence of a new technology in the choice set could induce or retard both retirement of existing capital and new purchases of capital. Likewise, consumer decisions regarding fuel/equipment choice (2) may be tied to projected intensity of use (3).

[2]Fisher and Kaysen (23) find that such things as the number of wired households per capita and the number of marriages are primary factors affecting purchases of new appliances.

operating costs (i.e., fuel cost) of the alternative choices, in addition to a comparison of the reliability, size, and efficiency of the alternatives. If a new technology is available such as a heat pump or color TV, its characteristics and costs would be expected to enter the consumer choice among possible appliances and their requisite fuels. Furthermore, the climate or region in which the appliance is used may affect the choice of fuel and appliance.[1] Once these two decisions have been made, the residential appliance stock is fixed in the short-run. We would expect therefore that the intensity of use of these appliances (capital utilization) would depend upon the cost of the fuel used by the appliance, the income and other characteristics of the residential user, the efficiency of the appliance and the weather (when space heating or air conditioning is involved). In similar fashion the factors affecting commercial and industrial demand can be identified.

An energy demand model should analyze these three sets of decisions while incorporating the characteristics of the energy user, the price and technical characteristics of the fuel and its requisite capital (including the fact of whether the capital represents a traditional or new technology) and the characteristics of the environment in which the fuel and capital are used. Furthermore since we are interested in policy uses of these models, we want the model to include variables subject to policy control that can be used to guide or affect the three energy-user decisions introduced above.

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[1] In cold climates, households seem to be willing to pay a higher capital cost for space heating equipment that uses a fuel with a lower operating cost. In warmer climates, households seem to prefer equipment with lower capital costs and higher operating costs, since the equipment is not used often. See (24).

Given this overview, let us look more formally at actual models and modeling techniques. The energy demand models that have been developed or are currently being developed treat all of these decisions but in varying degrees of effectiveness. The models can be categorized as follows:

1) Treatment of the relationship of demand for energy and for its requisite capital in the short-run and long-run

- Static, equilibrium models
- Dynamic, partial adjustment models
- Dynamic, multi-equation models

2) Treatment of fuel demand in relationship to other fuels and factors

- Single fuel demand models
- Interfuel substitution models.

The treatment of the interactive demand for energy and its capital (energy/capital complementarity) over time reveals most clearly how a given model deals with the three separate demand decisions. The static, equilibrium models, in general, focus upon the demand for a fuel only (decision 3) making it a function of fuel prices, user income, user characteristics and climate. Using the notation of the static models, we have therefore

$$q_t^* = q_t^*(P_t, y_t, w_y, SE_t); \qquad (1)$$

or in words, the desired demand for a fuel in time period $t(q_t^*)$ is a function of the price of that fuel and competing fuels (P_t), the income level or production level of the user (y_t), the relevant weather and climate conditions (w_t) and all other relevant socioeconomic factors (SE_t).[1]

[1] P_t, w_t and SE_t are vectors.

The static models assume instantaneous adjustment in the capital stock to changes in fuel demand; that is, if fuel demand increases, the requisite capital stock needed to burn it magically increases. As a result, all short-run and long-run responses are equivalent. The static equilibrium models are not designed to track short-run time-series variation in energy demand nor are they designed to incorporate the size or characteristics of the energy-using capital stock.

The dynamic, partial adjustment models make more explicit the interactive nature of the demand for energy and its requisite energy-burning capital. Rather than assuming instantaneous adjustment, partial adjustment models take account of possible short-run disequilibrium in the complementarity of energy and capital. As energy demand (decision 3) responds to changing economic conditions, the fixed capital stock cannot adjust as rapidly (decisions 1 and 2) due to time lags for adding new plant, equipment and/or appliances or for retiring undesired capital. Disequilibria result and energy demand can only partially adjust in the short-run until the capital stock adjusts. Using the notation of the partial adjustment models, we have therefore

$$q_t - q_{t-1} = \lambda(q_t{}^* - q_{t-1}); \qquad (2)$$

or in words, the change in actual demand from the time period t-1 to $t(q_t - q_{t-1})$ adjust partially (λ) to desired demand changes $(q_t{}^* - q_{t-1})$ where $q_t{}^*$ is defined in (1) above, q_t is actual demand in period t and λ $(0 < \lambda < 1)$ is the factor indicating how quickly (or how partially) actual demand adjusts to desired levels. In this case, short-run price and income demand responses are less than long-run responses when the capital stock fully adjusts to changed conditions. While partial adjustment models admit to the differences in short-run and long-run demand, they do not in general treat formally decisions 1 and 2; nor do they treat the characteristics and size of the capital stock.

The dynamic multi-equation models explicitly recognize the different characteristics of short-run and long-run demand. Rather than forcing a single equation to deal with the potential disequilibria in energy and capital demand, these models utilize explicit separate equations for each decision. The short-run equations model fuel demand conditional upon a capital stock fixed in size and technical characteristics, while the long-run equations analyze explicitly changes in the size and characteristics of that capital. Using the notation of the multi-equation models we have therefore

$$q_t = q_t^* = U_t(P_t, y_t, w_t, SE_t)K_t \tag{3a}$$

$$K_t = K_{t-1}(1 - \delta) + \Delta K_t \tag{3b}$$

$$\Delta K = f(P_t, CC_t, y_t, w_t, SE_t). \tag{3c}$$

In words, equation 3a treats actual short-run fuel demand as equal to desired short-run fuel demand which are both expressed as the utilization (U_t) of a given fuel-burning capital stock, K_t. The rate of utilization of the fuel specific capital stock (K_t) is a function of P_t, y_t, w_t, SE_t as defined above. Equations (3b) and (3c) treat the long-run issues when the fuel-burning capital stock is variable. K_t in any year is given by K_{t-1} minus retired fuel-burning capital δK_{t-1} (δ is the retirement rate) plus additions (ΔK_t) to the stock of capital that utilizes the particular fuel being analyzed. ΔK measures consumers choice or preference for a particular fuel and its requisite capital; if consumers find a given fuel desirable, based on its cost and the characteristics of its requisite capital, ΔK_t will be large. ΔK_t is shown in equation (3c) to be determined functionally by the relative costs of all possible fuels (P_t), the comparative characteristics of the capital required for the particular fuel (CC_t) and y_t, w_t and SE_t. CC_t clearly includes the capital costs and efficiencies of the appliances of the alternative fuels.

The second identifying characteristic of the body of models is treatment of fuel demand in relationship to competing fuels. The single fuel models analyze demand for one fuel (usually electricity) and treat competition from other fuels through cross-price elasticities. The interfuel substitution models deal with the competition from other fuels explicitly and in more detail; they are based upon the premise that the demand for any fuel cannot be adequately assessed without quantifying the price and capital cost and non-price competition posed by all alternative fuels and their respective fuel-burning appliances.[1]

Using these categories, Tables 1A-1C[2] present a fairly complete list of the residential, commercial and industrial energy demand models that characterize the capital stock of such models. Table 1C introduces an additional category -- industrial interfactor substitution models. These models treat demand for energy in conjunction with the demand for all other factors of production (capital, labor, energy and materials -- the KLEM models). Table 1 is not exhasutive; the discerning reader will notice that purely process, mathematical programming models and input-output models (17, 18, 25, 27, 28, 29) are not represented. For the most part, the models are econometric or combined econometric/process.

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[1] Many interfuel substitution models do not include these underlined factors, as discussed below.

[2] Unless referenced above (3, 4, 9, 23, 24, 26), the models' sources are given in (30-71).

In section BII below, I critique in more detail the models introduced here. Before coming to that critique, Table 2 attempts to summarize for the interested reader (as succinctly as possible) various aspects of selected models (mostly residential) from Table 1. I do not discuss Table 2 here.

II) Critique of the Models

Given the preceding examination of energy demand and an energy demand model, let us look more closely and more technically[1] at the models in Table 1. We find residential and commercial models (Tables 1A and 1B) separated into single fuel demand models and interfuel substitution models. For industrial models, the distinction is between single factor models (usually the factor is a single fuel) and interfactor substitution models where total energy demand is the factor considered along with capital services, labor services and materials. Few of the industrial interfactor substitution models focus on interfuel substitution within the energy factor; however, they could.[2]

In general, the single fuel residential and commercial demand models are more refined in their analytic structure and data base (26). They include a wider range of variables affecting short-run demand and more sophisticated model specifications.[3] The interfuel substitution residential and commercial models permit superior treatment of the competition to a given fuel from all other fuels and their respective fuel-burning equipment; however, the

[1] The following discussion employs descriptions and jargon that will be more familiar to economists knowledgeable in energy demand.

[2] Fuss (66) and Halvorsen (69) have done this.

[3] For example, Mount, Chapman and Tyrrell (MCT) incorporate variable elasticities that change with the level of the explanatory variables; if consumers are more sensitive to price effects at higher price levels, the MCT model would permit measurement of this effect. Anderson's residential analysis is extremely detailed in the specification of independent variables. The Taylor, Blattenberger and Verleger (TBV) analysis of residential electricity demand develops marginal and fixed electricity charges; this formulation permits a more refined analysis of the effect of electric utility declining block rate structures.

TABLE 1A: RESIDENTIAL ENERGY DEMAND MODELS

SINGLE FUEL MODELS	INTERFUEL SUBSTITUTION MODELS
STATIC	
Anderson (1972) (1973)	Anderson (1973)
Cargill and Meyer (CM) (1971)	
Chern (1976)	
Griffin (1974)	
Halvorsen (1973)	
Houthakker (1951)	
Wills (1977)	
Wilson (1971)	
DYNAMIC, PARTIAL ADJUSTMENT	
Balestra (1967)	Baughman/Joskow (B/J) (1974, 1975, 1976)
Berndt and Watkins (BW) (1977)	Federal Energy Administration Project Independence Evaluation System (FEA/PIES), (1974, 1976)
Halvorsen (1973)	
Houthakker, Verleger, Sheehan (HVS) (1974)	
Mount, Chapman and Tyrrell (MCT) (1973)	
Mount and Chapman (MC) (1974)	
Taylor, Blattenberger, Verleger/ DRI (TBV) (1977)	
DYNAMIC, MULTI-EQUATION	
Acton, Mitchell and Mowill (AMM) (1976)	Erickson, Spann and Ciliano (ESC) (1973)
Fisher and Kaysen (FK) (1962)	MIT/Hartman (MIT/H) (1978)
Taylor, Blattenberger, Verleger/ DRI (TBV) (1977)	Oak Ridge/Hirst, *et al.* (OR/H) (1977, 1978)

TABLE 1B: COMMERCIAL ENERGY DEMAND MODELS

SINGLE FUEL MODELS	INTERFUEL SUBSTITUTION MODELS
STATIC	
Chern (1976)	
DYNAMIC, PARTIAL ADJUSTMENT	
Balestra (1967)	Baughman/Joskow (BJ) (1974, 1975, 1976)
Berndt and Watkins (BW) (1977)	Federal Energy Administration Project Independence Evaluation System (FEA/PIES) (1974, 1976)
Mount, Chapman and Tyrrell (MCT) (1973)	
DYNAMIC, MULTI-EQUATION	
	Oak Ridge/Jackson, et al. (OR/J) (1978)

TABLE 1C: INDUSTRIAL ENERGY DEMAND MODELS

SINGLE FACTOR (FUEL) MODELS	INTERFACTOR SUBSTITUTION MODELS
STATIC	
Anderson (1971)	Berndt and Wood (BW) (1974, 1975)
Baxter and Rees (BR) (1968)	Denny and Pinto (DP), (1975, 1976)
Fisher and Kaysen (FK)	Fuss (1975, 1977)
	Griffen and Gregory (GG) (1976)
	Halvorsen (1977)
	Humphrey and Moroney (HM) (1975)
DYNAMIC, PARTIAL ADJUSTMENT	
Chern (1975)	Baughman/Joskow (B/J) (1974, 1975, 1976)
Mount, Chapman and Tyrrell (MCT) (1973)	Economics Research Group (ERG) (1977)
DYNAMIC, MULTI-EQUATION	
	Economics Research Group (ERG) (1977)

TABLE 2: OVERVIEW OF DEMAND STUDIES

AUTHOR/ ANALYSIS	LEVEL OF ANALYSIS/ TYPE OF DATA	DEPENDENT VARIABLE	EXPLANATORY VARIABLES[a] P_0	P_S	Y	N	W	A	D	t	OTHER	FUNCTIONAL FORM/ ESTIMATION TECHNIQUE
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 50 STATES, 1969	ANNUAL CONSUMPTION PER FLEXIBLE (NEW) CUSTOMER IN KWH/CUSTOMER YEAR	X	X	X		X		X			LOG-LINEAR, OLS
	CALIFORNIA, ANNUALLY 1947-1969		X	X	X					X		
3) ANDERSON (1973)	RESIDENTIAL APPLIANCE, ELECTRICITY, GAS DEMAND 50 STATES, 1960-1970	•SHARES OF APPLIANCE STOCK BY ENERGY TYPE FOR VARIOUS USES	X	X	X		X		X			LOG-LINEAR, OLS AND GLS. STATIC AND DYNAMIC FORMULATIONS
		•DEMAND FOR ELECTRICITY/ HOUSEHOLD	X	X	X		X		X			
		•DEMAND FOR GAS	X	X	X		X		X			
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 = i, i = 1,...24, DESEASONALIZED	X	X	X					X	EMPLOYMENT OF PRODUCTION WORKERS IN MANUFACTURING, Y^2	24 HOURLY EQUATIONS; OLS
6) FISHER AND KAYSEN (1962)	RESIDENTIAL ELECTRICITY AND APPLIANCE DEMAND 47 STATES 1946 - 1957	DEMAND FOR ELECTRICITY IN THE SHORT RUN (KWH) GIVEN FIXED APPLIANCE STOCK	X		X			X	X		NUMBER OF WIRED HOUSEHOLDS, NUMBER 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.
		DEMAND FOR APPLIANCES IN THE LONG RUN	X	X	X	X		X				
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 CONSUMPTION OF ELECTRIC ENERGY/CUSTOMER	X	X	X		X	X	X	X	DEGREE OF URBANIZATION, APPLIANCE PRICES.	STATIC EQUILIBRIUM MODEL. LOG-LINEAR, 2SLS, IV FOR STATIC EQUATION USING DATA 1961 - 1969.
9) HOUTHAKKER (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) P_0 = GAS PRICE, P_S = PRICE OF SUBSTITUTE FUELS, Y = INCOME, N = POPULATION, W = WEATHER/TEMPERATURE, A = STOCK OF APPLIANCES
D = DEMOGRAPHIC/HOUSING CHARACTERISTICS, t = TREND.

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

TABLE 2: (cont.)

	PRICE SPECIFICATION b)	ELASTICITIES: OWN-PRICE L.R.	OWN-PRICE S.R.	CROSS-PRICE L.R.	CROSS-PRICE S.R.	INCOME	OTHER	STOCK TREATMENT	ADDITIONAL REMARKS
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 -.88		.13 .17		1.13 .34-.46	-.85 SIZE OF HOUSEHOLD .18 WINTER TEMPERATURE .83 SUMMER TEMPERATURE		SEPARATE ROWS OF RESULTS FOR ANALYSIS OF 50 STATES AND CALIFORNIA
3)	TEB (1000 KWH/MO) TGB (50 THERMS/MO)	-1.12 -2.75		.30 GAS NEGATIVE BUT INSIGNIFICANT FOR OIL, ELECTRICITY AND COAL		.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
4)	AVERAGE PRICE	ELASTICITIES VARY CONSIDERABLY BY STATE AND GROUPS OF STATES POOLED BY HOMOGENEITY IN WEATHER, GAS AVAILABILITY AND TIME PERIOD -.68	-.03						INCREMENTAL DEMAND ELASTICITIES SIGNIFICANTLY GREATER THAN TOTAL DEMAND ELASTICITIES. SUBSTITUTES ARE OIL AND COAL.
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	INEL.	INEL. -.16 TO -.25	INEL.		.07 TO .33 CURRENT AND PERMANENT INCOME IMPORTANT	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 CHANGES.
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 19[illegible]1. 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 EQUATION 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
D = DEMOGRAPHIC/HOUSING CHARACTERISTICS, t = TREND.

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

TABLE 2: (cont.)

AUTHOR/ ANALYSIS	LEVEL OF ANALYSIS/ TYPE OF DATA	DEPENDENT VARIABLE	EXPLANATORY VARIABLES[a] P_0	P_s	Y	N	W	A	D	t	OTHER	FUNCTIONAL FORM/ ESTIMATION TECHNIQUE
10) HOUTHAKKER, VERLEGER, SHEEHAN (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 TYRRELL (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 50 STATES AND WASHINGTON, D.C. 1955 - 1974	•RESIDENTIAL CONSUMPTION OF GAS, ELECTRICITY AND OIL BY STATE	X	X	X		X		X		LAGGED ENDOGENOUS VARIABLE	•LOG-LINEAR AND LINEAR TRADITIONAL FLOW ADJUSTMENT MODEL; LOG-LINEAR AND LINEAR KOYCK MODEL
		•APPLIANCE STOCK UTILIZATION RATES	X	X	X		X	X			LAGGED ENDOGENOUS VARIABLE	•LOG-LINEAR AND LINEAR FLOW ADJUSTMENT AND KOYCK MODEL
		•CAPITAL STOCK	X	X	X		X				LAGGED ENDOGENOUS VARIABLE, APPLIANCE PRICES	•LOG-LINEAR OLS, ERROR COMPONENTS MODEL USED THROUGHOUT.
14) WILLS (1977)	RESIDENTIAL ELECTRICITY DEMAND; CONSUMPTION DATA FOR 39 MASSACHUSETTS ELECTRIC UTILITY DISTRICTS AND 57 RESIDENTIAL RATE STRUCTURES, 1975	MONTHLY CONSUMPTION 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			LINEAR, LOG-LINEAR OLS

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

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

TABLE 2: (cont.)

	PRICE SPECIFICATION b)	ELASTICITIES OWN-PRICE L.R.	OWN-PRICE S.R.	CROSS-PRICE L.R.	CROSS-PRICE S.R.	INCOME	OTHER	STOCK TREATMENT	ADDITIONAL REMARKS
10)	DIFFERENCES BETWEEN TEB 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	-.08			.10 S.R. 1.08 L.R.	ELECTRICITY FIXED CHARGE -.02 (S.R.) -.17 (L.R.)		REPORTED ELASTICITIES FOR FUEL DEMAND ARE THOSE FOR ELECTRICITY.
		-.12 TO -1.0	-.06 TO -.54			.0004 TO .38 (S.R.)	-.08 (L.R.) ELECTRICITY FIXED CHARGE	APPLIANCE STOCK VARIABLE A WEIGHTED STOCK USING "NORMAL" USE AS WEIGHTS	
			-.02 TO -.22		.02 TO .10	VARIES WIDELY BY APPLIANCE ALL INELASTIC HOWEVER			•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)	TEB FOR 500 KWH/MO	-1.33		0.31		-0.46		APPLIANCE STOCK IS A FUNCTION OF "LIFE STYLE." SEPARATE EQUATION, DEPENDENT VARIABLE: % HOUSES WITH AT LEAST 1 UNIT OF APPLIANCE i. (i = 1....6) 6 DIFFERENT CATEGORIES.	PRICE IS THE MAJOR DETERMINANT.

a) P_o = 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 (FPC) AND TGB IS TYPICAL GAS BILL (FROM BLS).

empirical implementation of them has been deficient to date: the analytic refinement and data base development of the single fuel models are generally missing. For the most part, interfuel comparisons are based only on operating costs, while the capital costs and technological characteristics of alternative fuel-burning devices have been ignored in the consumer choice decision 2 (except in 24 and 26). Furthermore, aggregate data has been used almost exclusively to estimate the interfuel substitution models, which can generate problems (27).

The industrial energy demand models (Table 1C) can attain greater analytic refinement because they utilize explicit production theory and assumptions of cost minimization to develop factor demand equations. Production theory in microeconomics permits an analyst to quantify just how a firm or industry combines factor inputs (capital, labor, energy and materials -- KLEM) to produce a product. The single factor (fuel) models utilize this approach focusing on only one factor -- energy or a particular fuel. The interfactor substitution models utilize the fact that the demand for a single factor (or fuel) and the potential disequilibrium in that demand are inextricably linked to the demands for all other factors of production through the technical constraints of the production function. For example, if there is disequilibrium in the demand for energy by a firm, it is likely that the demand for other factors will be in disequilibrium. The interfactor substitution industrial models explicitly incorporate this.[1]

As found with the residential models, the single factor (fuel) industrial demand models also demonstrate, in general, greater refinement and disaggregation[2] when compared to the interfactor substitution models. The interfactor

[1] See (73-74) for greater clarification.

[2] For example, the single fuel Baxter and Rees (BR) effort utilizes a specific form of a production function (generalized Cobb Douglas production function) to relate electricity demand to output and the factor prices of capital, labor, oil, gas, coal and electricity for 16 manufacturing groups in the U.B.K. BR rejected a priori the weak separability in capital, energy, and labor usually assumed by the interfactor substitution models. Anderson assesses separate demands for coal, coke, gas, oil and electricity in the primary metals industry. MCT incorporated their variable elasticity models mentioned above into aggregate industrial demand.

substitution models rest on a more solid theoretical foundation because they deal with the simultaneous (and interactive) demands for all factors through the production relationship (function). However, as with the residential and commercial interfuel substitution models, the industrial interfactor substitution models lack the refinement in independent variables used. The interfactor substitution models of BW, DP, ERG, GG, HM and Pindyck (see Table 1C) all deal at the aggregated factor demand levels of capital (K), labor (L), energy (E) and materials (M) -- the KLEM models.[1] Only Fuss and Halvorsen model and estimate K, L, E and M factor demand in addition to the interfuel substitutability within E for coal, liquid petroleum gas, fuel oil, natural gas, electricity and motor gasoline.

In terms of the treatment of intertemporal energy demand and its relation to the stock of fuel burning capital, examples of the static equilibrium models in Table 1 include the Anderson, Halvorsen, Houthakker and Wilson residential models, in addition to the Anderson, BR, Chern, FK, BW, DP, GG, Fuss, Halvorsen, HM and Pindyck industry demand models.

While these static models analytically ignore consumer energy decisions 1 and 2, the models have been useful. Anderson (31) experimented with both dynamic and static formulations and found that due to the relatively steady-state

[1]All of these efforts assume weak separability within the four factors and test various forms of separability for combinations of K, L, E and M. For the non-economist, we assume that any firm will try to minimize the costs of producing a given level of output. He will choose therefore a mix of K, L, E and M to minimize those production costs. Weak separability implies that the firm is characterized by a production relationship such that the mix of disaggregated factors (e.g., coal, LNB, petroleum, natural gas, etc. within E) within a single factor category can be chosen to minimize costs independent of the level of other factors used (e.g., K, L & M).

For the economist, assume for production function $F(x_1, \ldots, x_n)$ that the n inputs can be categorized into four mutually exclusive input categories -- capital (K), labor (L), energy (E) and materials (M). The production function $F(x)$ is said to be weakly separable with respect to the partition KLEM if the marginal rate of substitution between any two inputs x_i and x_j from K, L, E or M is independent of the quantities outside that group, i.e.,

$$\frac{\partial(F_i/F_j)}{\partial x_k} = 0 \text{ for } i, j, \varepsilon, K, L, E, \underline{or}\ M \text{ and } k \notin \text{ that group.}$$

trending of the important causal variables in the 1960's, either the static or dynamic partial adjustment versions of demand models provided essentially the same parameter estimates and simulation performance. The static demand models in price and income predicted well (particularly for residential energy) because all underlying variables were fortuitously trending together, including absolute and relative prices, appliance stocks, technological characteristics and utilization rates.

However, the equivalence of static and dynamic model results disappears in periods when smooth trending in the economic time series is lacking, such as the 1970's. The static equilibrium models then become less useful. The reason, as seen above, is that as energy demand responds to changing non-steady state conditions, the fixed capital stock cannot adjust instantaneously due to time lags for adding new plant and equipment or retiring undesired plant and equipment. Partial-adjustment disequilibrium energy demand models were introduced to take account of this short-run disequilibria. As seen in Table 1, such partial adjustment formulations are built into the Balestra, BW, Halvorsen, HVS, MCT, MC, B/J, FEA/PIES and Anderson residential models; all the commercial demand models except OR/J; and the MCT and ERG industrial demand models.

While the partial-adjustment models admit the crucial interaction of demand for energy (fuels) and its requisite capital, they still leave the relationship implicit. Furthermore, they impose in most cases a constant relationship between the short-run and long-run elasticities for all exogenous variables,[1] and they still do not permit explicit identification of long-run and short-run policy variables. To avoid these problems one must resort to separate multi-equation treatment of the long-run and short-run, treating short-run demand as the utilization of a given capital stock and the long-run demand as determining changes in the size and characteristics of that fuel burning

[1] $e_{LR} = e_{SR}/(1-\lambda)$. See (42) for a development of this.

capital stock. Such a multi-equation approach has been built into the AMM, FK, TBV[1], OR/H and the proposed MIT/H residential demand models; the OR/J commercial demand models.

To summarize, the various vintages of energy demand models in Table 1 can be categorized by treatment of factor (fuel) demand and by treatment of the capital/energy complementarity over time. Let us now introduce several important model considerations and discuss how well the models in Table 1 treat them.

- Behavioral and Technological Specification

How well have the assembed models analyzed demand behavior and technological facts? While the static and partial adjustment dynamic models were useful analytical tools when first developed, they do not explicitly capture the dynamic differences between the determinants of short-run and long-run energy demand. These models treat aggregate energy demand without examining explicitly the relationship of such demand to the underlying fuel-burning appliance stock. They implicitly assume a long-run equilibrium relationship of fuel demand to appliance/capital stock. However as seen above, in the short run, the capital/appliance stock is fixed and energy demand expresses itself as varying utilization rates of that stock. In the longer run the size and characteristics of the capital/appliance stock can and will vary. Different sets of decisions and decision variables are involved with the long run and short run and should be modeled explicitly. Furthermore, since the essence of long-run demand is alternations in the capital/appliance stock, explicit treatment of technological change and emerging technogies in an endogenous and/or exogenous fashion is important.

- Identification and Incorporation of Policy Issues and the Relevant Policy Tools/Variables.

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[1] TBV (44) develop both a multi-equation model and partial-adjustment model for residential energy demand and demonstrate that the estimated long-run and short-run elasticities are similar; however, the multi-equation model gives a much more theoretically sound specification of short-run and long-run behavior and policy options.

Since the major uses of the models discussed above include analytic understanding and policy assessment, the models should identify and incorporate policy variables. The short-run policy tools should deal with energy conservation and factors affecting appliance stock utilization (e.g., thermostat controls, 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 residential, commercial and single-fuel industrial models introduced 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, demographic variables and technology variables. Which variables are incorporated into selected models is detailed somewhat in Table 2. The population, weather/climate and demographic variables clearly are not easily-used policy tools. The presence of an income variable in the residential demand models provides only a limited policy tool.

The own-fuel and substitute-fuel prices are clearly important policy tools that can be affected through such tings as BTU taxes. All of the models utilize own price. Those analyses which do not include substitute prices suffer considerably, including the Balestra, Griffin, and HVS residential models. FK do not include gas price in short-run residential demand, but they base its absence upon assumed zero cross-elasticity. The work of other residential analysts indicate such an assumption may be wrong. Most of the remaining residential and commercial electricity studies include gas as a substitute price; however, other substitutes include oil and coal. Only the Anderson residential and industrial models and BR and Chern industrial models include these substitute prices. Furthermore, although all studies include own price, only AMM, TBV, and Wills explicitly deal with the declining block rate tariff structure of electricity through a marginal price and a fixed charge. The remaining analyses use average price, or typical electric bill (TEB). This treatment of marginal and fixed charges permits analysis of proposed electricity rate restructuring such as rate leveling and rate structure inversion. Finally, none of the residential, commercial and industrial single-fuel studies deal with the need for treating natural gas prices with 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 industrial interfactor substitution models, for the most part, utilize an aggregate energy price for manufacturing as a whole. Only Fuss and Halvorsen deal with interfuel substitution. The presence of capital user costs and labor and materials prices does permit policy assessment of the effects on factor demand of BTU taxes and other fuel price policies, in addition to policies affecting the cost of capital (e.g., accelerated depreciation allowances) and labor (e.g., social security taxes).[2] However, all of these policy assessments should be performed within an interfuel substitution model such as utilized by Fuss and Halvorsen.

The greatest policy inadequacy of the models of Table 1 is the lack of technological specificity. Greater analysis of capital/appliance stock characteristics (efficiency, size, characteristics and uncertainties of new technologies) and capital/appliance costs are desirable in both the short-run and long-run for all demand models. In the long-run technological characteristics of old and new technologies and the cost of disaggregated capital services are crucial to consumer choice among fuels and appliances; they should be taken more explicitly into account. Within the residential and commercial

[1] See Taylor Blattenberger Verleger (44), although Berndt (75) demonstrates this effect may be small, at least for electricity.

[2] See, for example, Wood (76).

models, FK, MCT, and TBV do include appliance prices. However, they are single fuel models and it is important to treat interfuel comparison of appliance characteristics and capital costs for consumer choice in the long-run. Such a long-run interfuel comparison is addressed only in multi-equation efforts of OR/H and MIT/H. The industrial demand models as a whole are deficient in treating the technological characteristics of the capital stock in the short-run and in the long-run. Technological change in the single factor industrial models is at best proxied by time (Anderson) and the coal consumption of particular industries (BR). Within the industrial interfactor substitution models technological change is treated only in ERG.

Finally some policy proposals such as peak load pricing and the penetration of solar photovoltaic installations into the residential sector really require seasonal and time-of-day modeling. Few models have achieved that level of refinement. The AMM residential model utilizes 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 for all user sectors (residential, commercial and industrial) and could be utilized to analyze the effects of hourly peak load pricing. Beyond these two models, there is nothing that builds time-of-day pricing issues into a general energy demand model.[1]

- Extent of Model Disaggregation

Certainly the minimal level of demand disaggregation is the residential, commercial and industrial sectors discussed above. However, to fully treat the long-run/short-run behavioral differences and to incorporate technological and policy variables, the 2 to 3 digit SIC level within the commercial and

[1]There is, however, a growing literature on isolated time of day studies. See (77-79). Time of day effects are currently being introduced into the MIT/H effort (26).

industrial sectors is desirable.

In terms of geographical disaggregation, for the purposes of most policy analysis and simulation experiments, disaggregation to state level seems more than sufficient. Most of the residential and commercial models in Table 1 are disaggregated to that level.[1] The industrial interfactor substitution models are generally estimated for the U.S. or Canada as a whole. Such levels of geographical aggregation are probably permissible for assessing questions of emerging technologies within the industrial sector where weather/climate have less of an effect upon the economic desirability of those potential technologies for process uses. However, regional differences in relative prices could induce differential patterns of technological change and it may be important to deal with it.

- Data and Econometric Techniques Utilized

Many of the above model inadequacies reflect the fact that data does not exist to perform the specifications desired. The most commonly utilized data for residential, commercial and single fuel industrial analysis have been pooled annual time-series of state cross-sections. For the interfactor substitution models, national time series or international cross-sections (Pindyck) have been utilized.

Cross-sectional data within a country is generally undesirable because locational effects overstate elasticities, particularly price elasticities (80). International cross-sections are likewise undesirable because structural differences bias elasticities away from zero (80). National time series avoid the cross-sectional difficulties but suffer from multi-collinearity and limited degrees of freedom. The pooled time-series of cross-sections avoid some of these difficulties particularly given the available econometric techniques

[1] More detailed and refined analytic results and policy assessments are possible if the geographical units are utility areas, meter readbook areas. cities, and SMSA's (such as the works of AMM and Wills).

for correcting pooling problems.

However, even this data has difficulties for dealing with some of the behavioral models. For example, the models of individual consumer choice underlying most of the interfuel substitution models require more refined micro data such as that of the Midwest Research Institute (81). Adequate modeling of the differential short-term and long-term residential energy demand behavior requires detailed appliance stock information such as the data initially developed by TBV (82); this data requires improvements (83). Such appliance stock data would be extremely useful for analyzing commercial and industrial demand; it is virtually non-existent. Furthermore, greater regional, sectoral (i.e., 2-3 digit SIC) and factor (i.e., breaking out elements of capital and energy) disaggregation is necessary to eliminate the above mentioned inadequacies in industrial demand modeling.

The appropriate statistical/econometric techniques for residential demand are usually 2SLS, instrumental variables (IV), GLS, and/or an error components model. Iterated 3SLS is usually used for the industrial interfactor substitution models. In some cases, OLS has been used in generating results not widely different than those from a consistent technique (e.g., Mount Chapman Tyrrell long-run residential elasticities). Parameter estimation in the presence of serial correlation and a lagged endogenouse variable (in the partial-adjustment models) are extremely sensitive to assumed stochastic specification, sample period definition and variable definition.

It is usually not possible in original model-building efforts to subject the 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 (80) 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 defintion of variables lead 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 estimated the Anderson model for different regions to correct for regional differences (such as the price 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 zero; 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 partial-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. One must still be careful to correct for cross-sectional variations (based on 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.

III) Research in Progress -- Advanced Multi-Equation Models Currently Being Used or Developed.

It should be clear from this critique that the dynamic, multi-equation demand models that are disaggregated by fuel end-use and that incorporate the technical characteristics of the fuel burning capital stock reflect the current direction of model development. Before we formalize such frontier energy demand model characteristics in Section C, let us briefly mention four models as examples. They are the Oak Ridge National Laboratory/Hirst (OR/H) and Massachusetts Institute of Technology/Hartman (MIT/H) models of residential energy demand, the Oak Ridge National Laboratory/Jackson (OR/J) model of commercial energy dmenad and the Economic Research Group (ERG) model of industrial demand. The OR/H and OR/J models are mature models currently in policy use; the MIT/H and ERG models are in development stages.

The MIT/H residential model differentiates short-run and long-run demand as in equations 3a-3b for the fuel categories and fuel end-uses in Table 3A. The utilization rates of the stock of appliances for the end-uses in Table 3A are made functions of fuel costs, income and weather (84-85). The long-run model of consumer choice among fuels and fuel-burning capital (equation 3C) utilize a comparison of the operating costs of alternative fuels, the capital costs and technical characteristics of alternative equipment, the personal characteristics of the consumer, the the demographic/socioeconomic characteristics of the environment in which the choice is made. Multinomial logit and covariance probit are two of the technical methods of modeling consumer choice that are being examined. Particular focus is being paid to the explicit treatment of new technologies (26).

The MIT/H model is disaggregated by end-use and fuel-type. While the analytic tools exist to do econometric modeling, major data efforts are required and are currently underway (83, 86).

The OR/J commercial energy demand model is a multi-equation effort

TABLE 3A: ANALYTIC DISAGGREGATIONS OF MIT/H

RESIDENTIAL ENERGY DEMAND MODEL

TENTATIVE FUEL CATEGORIES	TENTATIVE FUEL USES
GAS	SPACE HEATING
OIL	WATER HEATING
ELECTRICITY	COOKING
COAL	AIR CONDITIONING
OTHER/NONE	CLOTHES DRYING
	REFRIGERATION/FREEZING
	OTHER

TABLE 3B: ANALYTIC DISAGGREGATION OF

OR/J COMMERCIAL ENERGY MODEL

END USE	COMMERCIAL SUBSECTOR
Space heating	Finance and other office-related activities
Cooling	Retail-wholesale
Water heating	Auto repair and garage
Lighting	Warehouse activities
Other	Educational services
	Public Administration
FUEL TYPE	Health care services
	Religious services
Electricity	Hotel-motel services
Natural gas	Miscellaneous commercial activities
Oil	
Other	

that models energy demand for fuel-types, end-uses and commercial subsectors identified in Table 3B. The model formulates demand as a utilization rate of the energy using capital (equation 3a) and estimates the capital stock by relating it to commercial floor space (57).

The disaggregated OR/J model structure is currently better than the data and econometric results used to quantify the model. One of the major problems faced by OR/J has been the paucity of necessary demand data. They have made important strides in developing the requisite disaggregated data (58). As a result of data inadequacies, OR/J has been forced to rely at times on ad hoc estimates and specifications; however, their efforts have indicated the directions of necessary data development.

The industrial demand models critiqued above have been farthest from the multi-equation, technologically specific ideal model hinted at above. Some extremely interesting and promising (yet tentative) research is underway for industrial energy demand which combines the following theoretical and empirical tools: a) traditional instanenous-adjustment interfactor (KLEM) substitution models (63, 64, 68, 70, 71) and extensions to interfuel substitution (66, 69); b) dynamic partial-adjustment interfactor substitution models (73, 74); c) long-run optimizing dynamic disequilibrium interfactor substitution models with internal and external costs of adjustment (87-90); d) demand models for quasi-fixed factors (i.e., capital and technology) (91-95); and e) econometric production modeling utilizing flexible functional forms (65, 92, 95). This is no small list of tools and I only mention them here for completeness. ERG (65) have utilized these tools in an attempt to specify a model of industrial demand based on a dynamic programming formulation. This formulation generates short-run energy demand functions similar to (3a) that take account of the demand for other variable factors (labor, materials) given the fixity of the size and characteristics of the capital stock. The formulation also generates long-run (optimal) demand equations for fuel-using capital.

The current ERG efforts remain tentative and rather theoretical; research is currently underway to yield a much greater level of empirical refinement and implementation, thereby meeting the desires for technological and policy specificity. These efforts fall into three categories. First, disaggregation of the KLEM elements is being sought, particularly for energy into a level of refinement found in Fuss (66) and for the capital stock into more detailed categories of productive building and equipment in addition to environmental capital. Such refinement will permit capital stock specific and fuel specific policy assessment within an econometric model permitting substitution and price sensitivity. Second, better treatment of technical progress is being examined. Specifications can be exogenous, treating technical progress through estimated declines in factor prices as discussed in ERG.[1] Specifications can also be made endogenous by relating the state of technology to R&D expenditures.[2] And third, improvements of U.S. and Canadian time series and cross-section data are being emphasized to do such analysis at the 2 and 3 digit SIC level.[3]

C) SUMMARY AND FORMALIZATION OF FRONTIER ENERGY DEMAND MODEL CHARACTERISTICS

While Section B has reviewed and critiqued the manner in which a number of models have analyzed the three decisions inherent in energy demand, this section summarizes and formalizes the characteristics that represent the most advanced or frontier energy demand models, according to four important characteristics:

- Explicit treatment of Long-run and Short-run Demand, with the purpose of identifying behavioral characteristics and policy variations specifically relevant to each.

As stated above, the demand for energy is a derived demand for the services that a given energy source and its fuel-burning capital provide. Demand

[1] ERG (65), pp. 108-111.
[2] ERG (65), Chapter 5.
[3] ERG (65), Chapter 6.

behavior and potential policy variables can be classified as short-run and long-run. In the short run, behavioral specifications and policy variables (for example, BTU taxes, thermostat controls, speed limits and peak load pricing) 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 technological characteristics of the capital stock are variable, the characteristics and availability of new technologies and interfactor/interfuel substitution (through changes in the capital mix) become relevant. As a result, in the long-run, capital and appliance efficiency taxes and standards, capital costs, and the demonstration of new technologies become relevant policy variables, in addition to the standard operating costs of the fuels.

Explicit multi-equation analysis of both the long-run and short-run with the incorporation of detailed technological and policy variables characterize frontier modeling efforts. This approach has argued for pushing the frontier in the direction of combining econometric and process models. Econometric energy demand models (particularly static and partial adjustment) have traditionally stressed the importance of income, energy prices and interfactor and/or interfuel substitution; however, they have suffered from aggregation in their efforts and the inability to explicitly treat capital stock characteristics and non-price policy variables. Optimizing process models have traditionally stressed the importance of capturing disaggregated technological characteristics and relationships; however, they have suffered from an inability to capture price effects and substitution results.[1] Both approaches represent fairly extreme

[1]It is interesting (yet understandable on reflection) to find that model reviews comparing the results of econometric, process/econometric and process models find that econometric models estimated with cross section data display the greatest price sensitivity and input-output process models display the least. Econometric models are built on the premise of substitutability and price response; input-output process models utilize for the most part fixed factor coefficients which assume, in the short-run, no price response. These results therefore say less about reality than they say about the inbred world views of pure econometric and pure process model approaches. A hybrid would avoid the extreme cases. See (96) for a review and comparison of (3, 9, 12, 15, 17, 18, 19, 21, 28, 50, 52, 57, 68, 71 and 97).

characterizations of reality. A hybrid approach is desirable, combining the behavioral formulations of econometric models with the technological and policy specificity of process models into a multi-equation model with separate equations explicitly focusing on short-run demand and long-run demand.

- Appropriate Level of Disaggregation of energy end-use, with the purpose of permitting technological specificity in treating fuels and the fuel burning capital stock.

Tables 3A and 3B indicated the level of analytic disaggregation in two multi-equation models, MIT/H and OR/J. Clearly the fuel burning capital (appliance) stock differs by end-use and any attempt to analyze specific efficiency standards/taxes on new technologies is most effectively conducted within disaggregated end use categories.

- Appropriate Treatment of New Technologies

The theoretical, empirical and case study literature[1] treating technological change, technological biases and emerging technologies is extremely rich yet fairly unresponsive to the specific needs of treating new technology emergence in and penetration into the residential, commercial and industrial user sectors. Technological specificity is crucial to realistically deal with such potential new technologies as solar photovoltaics or heat pumps. In order to treat the characteristics and uncertainties of new technologies and the policy tools to help guide new technology penetration, combined process/econometric models are required.

Techniques exist to deal with new technologies. The use of discrete choice models discussed below, in conjunction with a hedonic treatment (100-103) of traditional and new technologies seems very promising, particularly for the residential sector (for treating Decision 2). However, while generalized

[1]For several good reviews, see (98, 99).

logit and covariance probit avoid some of the difficulties inherent in using conditional logit for dealing with consumer choice, the treatment of new technologies in the residential sector is still not trivial.

Discrete choice modeling may be useful for a better treatment of emerging technologies in the industrial and commercial sectors; however, little work has been done to date in this regard. A potential alternative (discussed below) is greater disaggregation within the flexible[1] functional forms utilized in the interfactor substitution models.

- Utilization of Appropriate Models and Data for Residential Consumer Choice and for Dynamic Modeling of Industrial and Commercial Demand

Two bodies of theoretical techniques have been developed which have been and will continue to improve energy demand modeling: discrete consumer choice modeling and the flexibility functional forms utilized for production/cost duality.

Consumer choice was found important in Decision 2 of Section B. Conditional logit has traditionally been utilized extensively for the analysis of interfuel substitution in a partial-adjustment framework for residential energy demand and to a lesser extent for commercial and industrial energy demand. However, conditional logit as used in the literature suffers from a number of difficulties including: the imposition of constant cross-elasticities (24, 47, 48, 49, 104, 105); implied misspecification (104, 105); excluded variables; the restrictive underlying model of individual choice (104, 105); and use of inappropriate data (72). Such modeling of consumer choice could be improved by generalized logit formulations (104) or covariance probit formulations (106, 107). Furthermore, in keeping with the explicit dichotomization of short-run and long-run behavior, the choice methodologies should be applied to changes in the appliance stock rather than the actual stock (104, 105).

[1]For example, the translog, generalized Leontief generalized quadratic and/or generalized Box Cox.

For industrial demand, single equation equilibrium or partial-adjustment factor demand models characterize much of the early work in capital, labor and energy demand models. These models suffer from ignoring the interaction among the demands for all factors built into the equilibrium (63, 64, 66, 68, 70, 71) and partial adjustment (73, 74) interrelated factor demand models. However, these dynamic interfactor substitution models still make adjustment costs exogenous. Endogenous incorporation of adjustment costs in a dynamic programming setting (87-90, 65) in addition to a more disaggregated treatment of factors of production through the use of flexible functional forms (95, 108-110) would be extremely useful.

Given these characteristics of frontier models, let us close by formalizing them -- with the notation of theoretical microeconomics. For continuity, let us start with traditional consumer and producer theory because they are the basis of much of the early static energy demand models found in Section B. Traditional consumer and producer theory utilizes constrained optimization to generate product and factor demand curves. Let q be an n vector of final goods and services and p be the corresponding price vector. Then for the consumer with income y we have

$$\text{Max } u(q)$$
$$\text{S.t. } p'q \leq y, \qquad (4)$$

yielding equilibrium product demand curves (as in Equation 1).

$$q_i = q_i(p, y) \qquad (4a)$$

Furthermore, let x be an m vector of factors of production[1] and w be the corresponding factor price vector. Then for the producer of j, with production function $q_j(x)$, we have (using cost minimization)

[1]The statement of utility and production can be traditional or can utilize the more flexible functional forms such as the translog, generalized Cobb Douglas, generalized Leontief, generalized square root quadratic or the generalized Box-Cox. See for example (95).

$$\text{Min } w'x \qquad (5)$$
$$\text{s.t. } q_j(x) \geq q_j$$

yielding equilibrium product demand curves (like equation 1)

$$x_i = x_i(w, q_j) \qquad (5a)$$

For the multi-equation approach desired, these traditional formulations can be more usefully respecified using production/cost and utility/expenditure duality. Using production/cost duality, the cost function is given by

$$C(q_j, w) = \underset{x}{\text{Min}} \{w'x \mid q_j(x) \geq q_j\}, \qquad (6a)$$

and the profit function is given by

$$\Pi(p_j, w) = \underset{q_j, x}{\text{Max}} \{p_j q_j - w'x \mid q_j(x) \geq q_j\} \qquad (6b)$$

Using Shepherd's Lemma or Hotelling's Lemma, the factor demand equations are obtained.[1] They are identical to the form of (5a), hence Equation 1.

Likewise[2] using utility/expenditure duality, the indirect utility function is given by

$$\nu\ (p, y) = \text{Max } \{u(q) \mid p'q \leq y\} \qquad (7a)$$

while the expenditure function is given by

$$e\ (p, u) = \underset{q}{\text{Min}} \{p'q \mid u(q) \geq u\} \qquad (7b)$$

Analogous to producers theory, the Hicksian and Marshellian demand curves are obtained from differentiating the expenditure and indirect utility functions.[3] Finally, as with traditional theory, the flexible functional forms[4] can be used for (6a), (6b), (7a), and (7b).

The demand equations that are generated from (6a) - (7b) are still equilibrium (the basis for Equation 1) and require one more development for a

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[1] See (91, 92, 93).
[2] See (91).
[3] See (91).
[4] See (91, 95).

dynamic multi-equation disequilibrium formulation that will effectively dichotomize the short-run and long-run along the lines discussed above.

For brevity in developing the notation, I treat only production. The results are extendable to utility. Let k represent a vector of fixed or quasi-fixed inputs (including, say, the state of technology). The production function becomes

$$q_j = q_j(x, k) \tag{8a}$$

and the "variable profit function"[1] is defined by

$$\Pi (p_j, w, k) = \underset{q_j, x}{\text{Max}} \{p_j q_j - w'x \mid q_j(x, k) \geq q_j\}$$

$$= p_j \cdot s\ (p_j, w, k) - w'd\ (p_j, w, k) \tag{8b}$$

while the "variable cost function" is given[2] by

$$C(q_j, w, k) = \underset{x}{\text{Min}} \{w'x \mid q_j(x, k) \geq q_j\}$$

$$= w'h\ (q_j, w, k) \tag{8c}$$

Hotelling's and Shepherd's Lemmas are equally applicable to the "variable" functions yielding short-run factor demand equations, conditional upon the fixed factors. For example,

$$\frac{\partial C}{\partial w_i} = x_i = h_i(q_j, w, k); \tag{9a}$$

the factor demand for x_i is conditional upon output q_j, factor prices w and the vector of fixed factors k. Likewise for consumer demand, one can obtain demand equations conditional upon income, prices and fixed factors k',

$$q_i = q_i(y, p, k') = U(y, p)\ k' \tag{9b}$$

[1]See (92, 93). In (8b) s is the industry supply function and d is the vector-valued, input demand function (92).

[2]See (92, 93). In (8c) h is the vector valued factor demand function (92).

The second equality in equation (9b) reflects the fact that short-run demand can be written (and conceived of) as the utilization rate U (conditional in y and p) of the vector of capital k'.

Three of the major characteristics of frontier energy demand modeling are now formally accessible.

1) Explicit Dichotomization of the Short-run and Long-run.

Demand equations (9a) and (9b) are clearly short run (the basis for equation 3a of Section B). Conditional on the stock and characteristics of fuel burning capital, demand for energy is analytically determined given equational forms for h_i and q_i. Long-run demand equations will deal with changes in k and k', both in terms of size and characteristics (equations 3b and 3c).

2) Appropriate treatment of New Technologies

The demand equations (9a) and (9b) are perfectly flexible as to the technological and policy specificity applied to the fixed capital stocks k and k'. Likewise, models of changes in k and k' can be as disaggregated as desired. Hence, there is room for as much incorporation of the technological refinement and disaggregation of process models as desired or deemed appropriate.

3) Utilization of Appropriate Models and Data for Consumer Choice and for Dynamic Modeling of Commercial and Industrial Demand

Hedonic consumer choice models should be used in addressing choices in the long-run changes in the consumer fixed capital k'. While such choice models may be useful for industrial and commercial demand, it may be possible to utilize dynamic general disequilibrium factor demand models to deal simultaneously with the short-run and long-run demand characteristics. Furthermore, appropriate treatment of all substitute and complement prices (p, w) is desired, particularly the declining block rate schedules of electricity.

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