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An Engineering-Economic Model of Residential Energy Use

Eric Hirst
William Lin
Jane Cope

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OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

This report describes a comprehensive engineering-economic computer model used to simulate energy use in the residential sector from 1970 to 2000. The purpose of the model is to provide an analytical tool with which to evaluate a variety of conservation policies, technologies, and strategies for their impacts on residential energy use and fuel expenditures over time.

The present version of the model deals with energy use at the national level for four fuels (electricity, gas, oil, and other); six end uses (space heating, water heating, refrigeration, cooking, air conditioning, and other); and three housing types (single-family units, apartments, and trailers). Each of these fuel uses is determined for each year of the simulation as the product of:

1. stock of occupied housing units,
2. fraction of homes using each fuel for each end use,
3. average annual energy requirement for each type of equipment,
4. average thermal integrity for each housing type,
5. household usage behavior for each fuel and end use.

Simulations of energy use from 1960 to 1974 show that the model does an excellent job of forecasting historical fuel use data in aggregate, by fuel, and by end use.

The baseline forecast shows total fuel use growing from 17.6 GGJ (10^{18} J) in 1975 to 26.4 GGJ in 2000, with an average annual growth rate of 1.7%. The percentage of household fuel provided by electricity grows from 44% in 1975 to 56% in 2000. The percentages provided by all other fuels decline over time. Alternative high and low forecasts show a range in annual fuel use growth from 1975 to 2000 of 2.1 to 0.3%. In the high case, per household fuel use grows at 0.4%/year, whereas in the low case, per household fuel use declines 1.1%/year.

1. INTRODUCTION

This report describes the structure, inputs, and results obtained with a detailed engineering-economic model that simulates household energy use from 1970 to 2000. The purpose of the model is to provide an analytical tool with which to evaluate a variety of energy conservation policies and technological improvements with respect to their impacts on residential energy use and expenditures over time. The model, as presently constructed, deals with energy use at the national level for four fuels* (electricity, gas, oil, and other); six end uses (space heating, water heating, refrigeration,† cooking, air conditioning, and other); and three housing types (single-family units, apartments, and trailers). Household energy use (for each fuel, end use, housing type, and year) is derived as the product of several determining factors. These factors and their derivations are described in detail in this report.

The remainder of this section summarizes data on household energy use trends, patterns, fuel prices, and expenditures for the period 1950 through 1974. Section 2 describes the structure of the model. Section 3 compares the model's outputs with historical data from 1960 to 1974. Section 4 presents our baseline forecast, our high and low forecasts, and compares our forecasts with those developed by others. The final

*Unless otherwise noted, electricity use figures are in terms of primary energy; that is, they include losses in generation, transmission, and distribution. Figures for gas and oil, however, do not include losses associated with refining and transportation.

†The end use refrigeration includes both refrigerators and freezers.

section summarizes the key features, limitations, and assumptions in the model and briefly discusses our planned efforts to improve the model.

Table 1 shows residential fuel use* from 1950 through 1974† for electricity, gas, petroleum products (kerosine and fuel oil), and other fuels (coal, coke, LPG).[1-5] The overall annual growth rate (see Fig. 1)

Table 1. Household consumption of fuels: 1950 to 1974

	Electricity[a] (end-use)	Electricity[a] (primary)	Gas	Oil	Other[b]	Total
	(10^{18} J)					
1950	0.26	1.27	1.55	1.84	2.45	7.11 (19.8)[c]
1955	0.47	1.83	2.50	2.58	2.03	8.94 (21.3)
1960	0.73	2.54	3.58	3.07	1.06	10.25 (21.8)
1965	1.05	3.51	4.54	3.40	1.12	12.57 (22.3)
1970	1.68	5.65	5.67	3.67	0.92	15.91 (22.4)
1971	1.79	6.10	5.81	3.64	0.84	16.39 (22.6)
1972	1.92	6.51	5.96	3.77	0.96	17.20 (22.6)
1973	2.07	6.87	5.80	3.67	0.94e	17.28 (21.9)
1974	2.08	7.01	5.67	3.32	0.92e	16.92 (21.9)

[a]The first column treats electricity at the point of use. Numbers in the second column include energy losses due to electricity generation, transmission, and distribution.

[b]Other fuels include coal, coke, and LPG.

[c]Numbers in parentheses are percentages of total national fuel use.

Sources: references 1-5.

*For those who prefer British units, 1 Btu = 1055 J.

†Edison Electric Institute (EEI) (ref. 1) figures for residential energy use are increased by 4% each year (ref. 5) to account for gang-metered apartment units classified by utilities as commercial. For the same reason, American Gas Association (AGA) (ref. 2) figures for residential gas use are increased by 22% of AGA's commercial gas use figures. Residential use of petroleum products is taken as the sum of heating uses for kerosene and Nos. 1, 2, and 4 distillate fuel oils (ref. 3), based on conversations with staff in the Bureau of Economic Analysis and ref. 5. Residential use of other fuels is from refs. 4 and 5.

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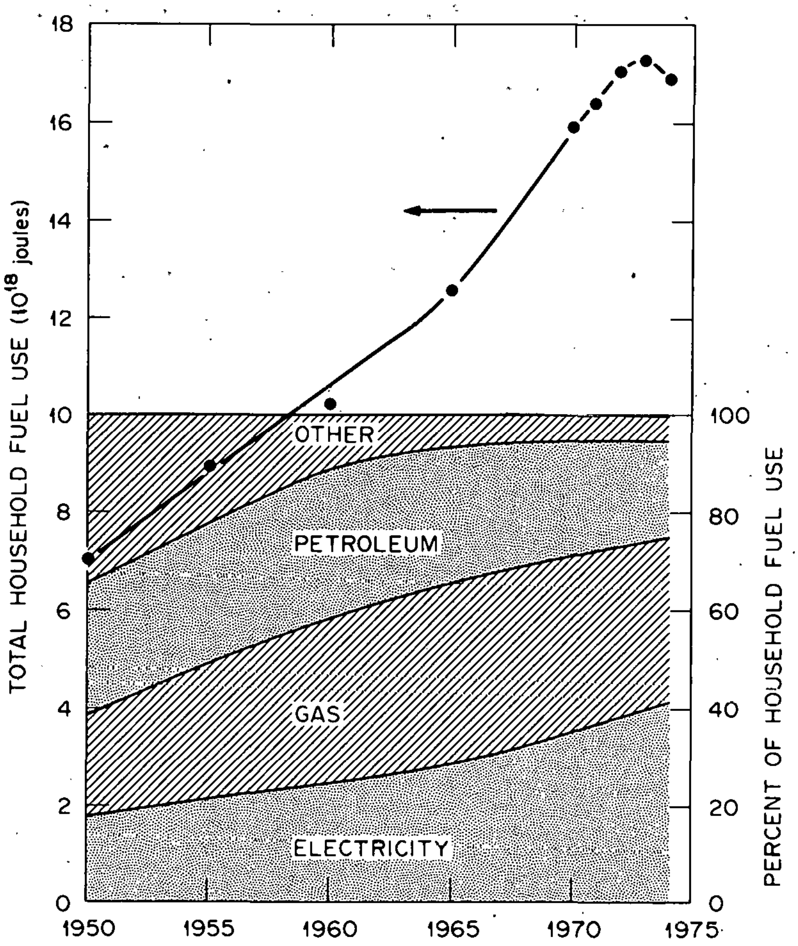

Fig. 1. Household fuel use: 1950-1974.

during this 24-year period in energy use was 3.6%, nearly double the growth rate in household formation (2.0%). However, during recent years, growth in fuel use has been much less: 1.5% per year between 1970 and 1974 and -2.1% between 1973 and 1974.

The distribution of fuels among the total changed dramatically during these 24 years, as shown in Fig. 1. In 1950, coal and coke accounted for more than one-third of household fuel use, while in 1974 these fuels accounted for only 2% of the total. Petroleum's share of the total also declined, from 26% to 20%. Electricity, on the other hand, increased its share from 18% in 1950 to 41% in 1974. The share accounted for by gas increased from 22% to 34% during this period.

Table 2 summarizes household expenditures on fuels for this 24-year period.* In constant dollar terms (i.e., removing the effects of inflation by dividing each current dollar amount by the Consumer Price Index[9]), household expenditures on fuels increased at an average annual rate of 4.1%. However, between 1970 and 1974 the growth rate was much higher at 6.2% per year, and between 1973 and 1974 expenditures jumped 10.5%.

Table 2. Household expenditures on fuels: 1950-1974

	Total fuel expenditures (billions of dollars)		Fuel expenditures as a percent of total PCE[b]
	Current dollars	1967 dollars[a]	
1950	6.5	9.0	3.4
1955	9.4	11.7	3.7
1960	12.4	14.0	3.8
1965	15.7	16.6	3.6
1970	21.5	18.4	3.5
1971	23.3	19.2	3.5
1972	25.5	20.4	3.5
1973	28.2	21.2	3.5
1974	34.6	23.4	4.0

[a]The constant dollar numbers are obtained by dividing the current dollar numbers by the Consumer Price Index from ref. 9.

[b]PCE is Personal Consumption Expenditures from ref. 7.

Sources: references 1, 2, 5-9.

*Electricity prices are from ref. 1; gas prices from ref. 2; petroleum prices (represented by No. 2 fuel oil) from ref. 6. Prices for "other" fuels are inferred from expenditure data in refs. 5 and 7 and consumption data in refs. 4 and 5. See ref. 8 for a discussion of detailed trends in residential fuel prices and expenditures from 1950 to 1974.

Figure 2 shows expenditures on fuels and trends in fuel prices[1,2,5-8] for this period. Generally, prices were declining or stable until 1972; since then prices for all fuels, especially petroleum products, have risen. The sharp increases in fuel prices in the early 1970s increased dollar expenditures and reduced growth in demand for household fuels.

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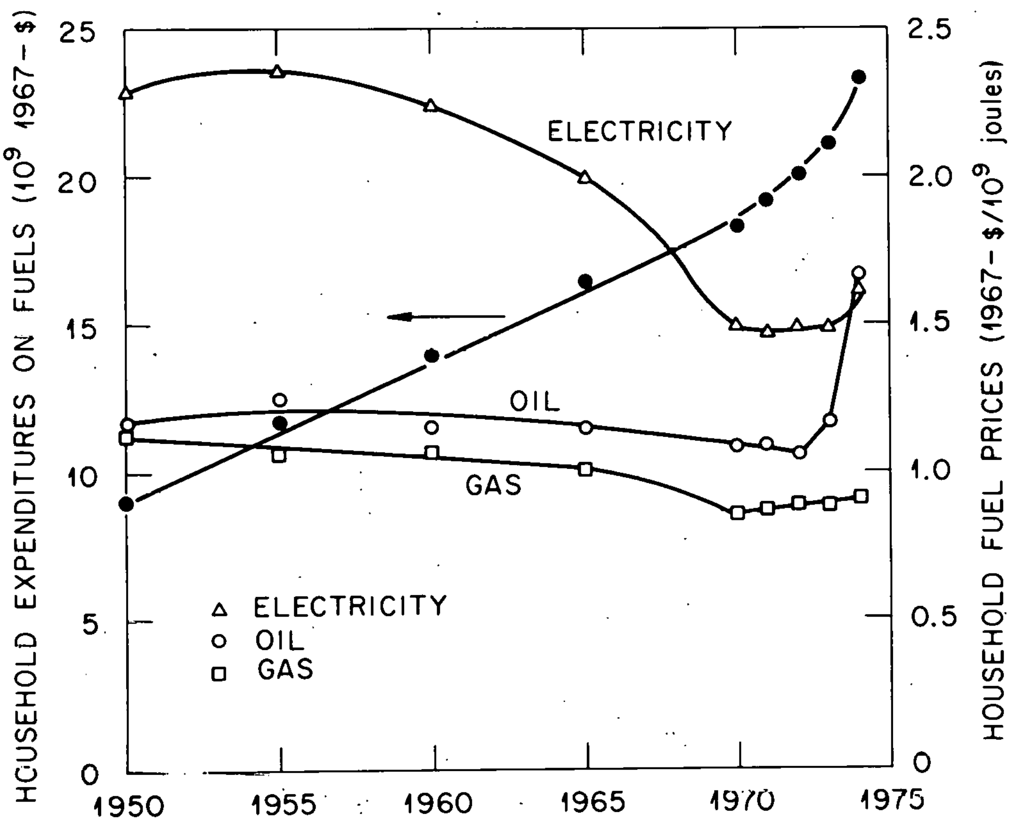

Fig. 2. Household expenditures on fuels and fuel prices: 1950-1974.

Household expenditures on fuels, as a percentage of total personal consumption expenditures (PCE),[7] remained roughly constant between 1950 and 1973 at about 3.6% of PCE. However, between 1973 and 1974 the percentage jumped from 3.5% to 4.0% due to the sharp increases in fuel prices shown in Fig. 2.

Figure 3 shows household energy use and fuel expenditures <u>per household</u>.[8] Until 1972, fuel consumption grew nearly twice as fast as

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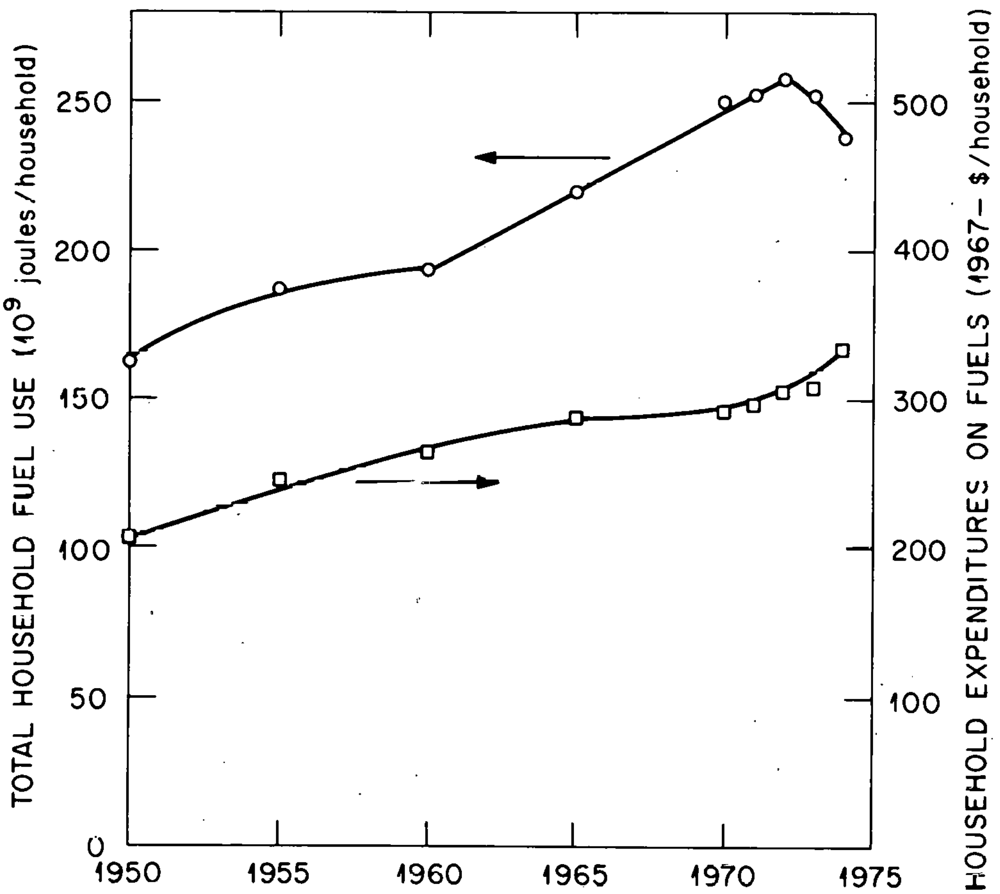

Fig. 3. Per household fuel use and fuel expenditures: 1950-1974.

the number of households. Between 1972 and 1974, however, fuel use per household dropped suddenly after two decades of steady growth. Between 1950 and 1970, constant dollar fuel expenditures per household grew slowly at an average annual rate of 1.8%; between 1970 and 1974 the rate increased to 3.6%.

Table 3 shows the types of fuel used for space heating, water heating, and cooking, and the fraction of homes with air conditioning for 1950, 1960, 1970, and 1973.[10-12] Space heating (the largest household user of fuel) choices shifted sharply between 1950 and 1973: the fraction of homes heated by coal dropped from 34% to 1%, and the fractions of homes heated by electricity and gas increased sharply. This shift in heating fuel accounts for much of the change in aggregate fuel use noted in Table 1 and Fig. 1.

Table 3: Household equipment ownership: 1950, 1960, 1970, 1973[a]

	Electricity	Gas	Oil	Other	None
	(percent)				
Space heating					
1950	0.7	26.4	22.5	49.0	1.4
1960	1.8	43.2	32.5	21.9	0.9
1970	7.7	55.2	26.0	10.5	0.6
1973	10.4	55.5	24.9	8.6	0.7
Water heating[b]					
1960	20.4	47.5	11.7	9.3	10.9
1970	25.4	55.2	9.8	6.0	3.8
1973	28.4	54.5	9.2	5.2	2.7
Cooking					
1950	15.0	51.5	6.7	26.5	0.3
1960	30.9	51.5	1.1	16.1	0.5
1970	40.7	49.2	0.5	9.4	0.3
1973	44.7	46.0	0.1	8.6	0.5

	Electricity: Room units	Electricity: Central	None
Air conditioning			
1950	0.7	0.1	99.2
1960	10.5	1.9	87.6
1970	25.0	10.7	64.3
1973	30.1	16.8	53.2

[a] The number of households (occupied housing units) was: 42.1 million in 1950, 53.0 million in 1960, 63.4 million in 1970, and 69.3 million in 1973; from refs. 10 and 11.

[b] The Census Bureau did not report ownership of water-heating equipment for either 1950 or 1973. The 1973 estimates shown above were derived from trends in water heater ownership for 1970-1974 reported in ref. 12.

Source: references 10-12.

Water heating, the second most important use of fuel, showed similar shifts: increases in electricity and gas and declines in other fuels. For cooking, electricity captured an increasing share of the market (up from 15% in 1950 to 45% in 1973) at the expense of all other fuels. The fraction of homes with electric air conditioning increased dramatically during this period — from less than 1% in 1950 to almost 50% in 1973.

Information on household ownership of fuel-using equipment,[10-12] energy use per household for each type of equipment,[13,14] and control totals for each fuel allow us to estimate quantities of fuel used by end use.* Estimates for 1970 are shown in Table 4. Space heating accounted for 56% of household fuel use and water heating accounted for another 14%. Thus these two uses account for more than two-thirds of total fuel use. Adding energy use for refrigeration (the third largest fuel use) brings the subtotal to almost 80%. Thus cooking, air conditioning, lighting, clothes washing and drying, and operation of small appliances together account for only one-fifth of the total.

Table 4 also shows differences among fuels in their allocation among end uses. Except for electricity, space heating accounts for the major share of each fuel, ranging from 70% for gas to 93% for other fuels (coal, coke, wood, and LP gas); space heating accounts for only 18% of electricity used in homes.

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*Estimates of 1970 fuel use per household for each fuel/end use combination from ref. 13 were scaled up so that these derived totals matched control totals for each fuel reported in Table 1. For electricity, gas, and other fuels, the adjustments were minor. For petroleum, however, we increased the figures from ref. 13 by almost 50%. Dole's assumption that oil heating systems operate with an efficiency of 55% is apparently much too high. Our control totals suggest an efficiency of about 40%.

Table 4. 1970 household fuel use by fuel and end-use

	Electricity	Gas	Oil	Other[a]	Total
	(10^{18} J)				
Space heating	0.84	3.92	3.39	0.82	8.97 (56)[b]
Water heating	0.88	0.98	0.28	0.07	2.21 (14)
Refrigeration	1.22				1.22 (8)
Cooking	0.39	0.32		0.03	0.74 (5)
Air conditioning	0.70				0.70 (4)
Other	1.62	0.45			2.07 (13)
Total	5.65	5.67	3.67	0.92	15.91
	(35)[b]	(36)	(23)	(6)	

[a]Other fuels include coal, coke, and LPG.

[b]Numbers in parentheses are percentages of the grand total, 15.9×10^{18} J.

Sources: references 1-3, 5, 13.

In summary, Tables 1-4 and Figs. 1-3 show that the period 1950 to 1974 was one of initial stability and final turbulence with respect to household energy use and expenditures. Until 1970, increases in fuel use and expenditures were steady. Since then, fuel use and expenditures have changed sharply from their pre-1970 trends, due to sudden increases in fuel prices and declines in per capita income.

2. STRUCTURE OF THE MODEL

Figure 4 is a schematic diagram of the model. The first submodel estimates stocks of occupied housing units by type (single-family units, apartments, and trailers) for each year of the simulation. Based on calculations of household formation and retirements from the existing stock of occupied units, new construction requirements are calculated each year to ensure that the stock of occupied housing matches demand. The housing model used here was originally developed for the U.S. Forest Service.[15] It has since been modified slightly at ORNL.

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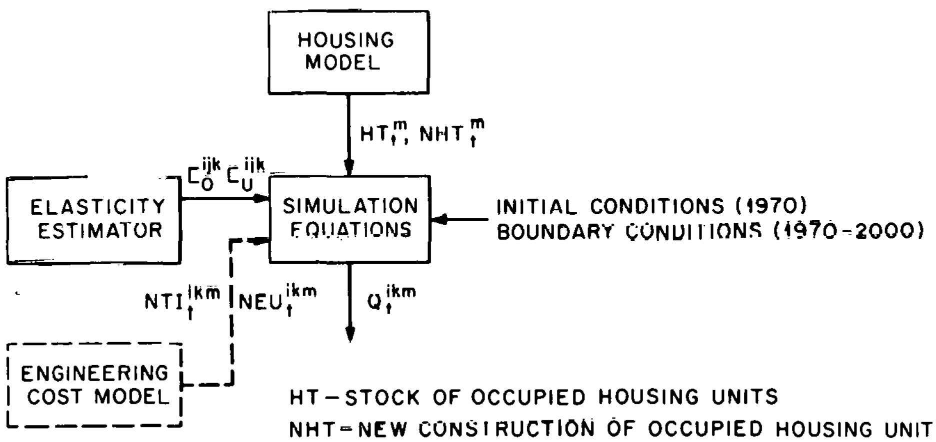

HT – STOCK OF OCCUPIED HOUSING UNITS
NHT – NEW CONSTRUCTION OF OCCUPIED HOUSING UNITS
E – ELASTICITY
Q – FUEL USE
NEU – ENERGY USE FOR NEW EQUIPMENT
NTI – THERMAL INTEGRITY OF NEW STRUCTURES

SUPERSCRIPTS
i – FUEL TYPE (4: ELECTICITY, GAS OIL, OTHER)
j – INDEPENDENT VARIABLE (4: PRICES OF ELECTRICITY, GAS, OIL; INCOME)
k – END-USE FUNCTION (6: SPACE HEATING, WATER HEATING, REFRIGERATION, COOKING, AIR CONDITIONING, OTHER)
m – HOUSING TYPE (3: SINGLE-FAMILY, MULTI-FAMILY, MOBILE HOME)

SUBSCRIPTS
O – OWNERSHIP
U – USAGE
t – TIME

Fig. 4. Schematic of residential energy use model.

The second component of the energy simulation is the elasticity estimator. This program calculates price and income elasticities* of the three major household fuels (electricity, gas, and oil) for each of the six end uses. Each elasticity is decomposed into two elements — an elasticity of equipment ownership (E_o) and an elasticity of equipment use (E_u). The first gives changes in equipment ownership in response to changes in fuel prices and incomes, whereas the second gives the responsiveness of equipment usage (with ownership held constant) to changes in prices and incomes. This submodel computes a total of 144 elasticities (short and long run for 3 fuels x 4 price and income variables x 6 end uses).

The third submodel, shown in dashed lines, will (when complete†) calculate unit energy requirements and initial cost for residential heating-ventilating-air conditioning (HVAC) equipment, appliances, and structures. These energy and cost figures will be estimated as functions of engineering design changes to increase energy efficiency. In the present version of the model capital costs do not appear, and energy use values for each type of equipment and structure are exogenously specified.

The residential energy use simulator combines outputs from the housing, elasticity, and engineering cost submodels with appropriate initial conditions for 1970 and boundary conditions for the period 1970

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*Elasticity is defined as the percentage change in the dependent variable (y) due to a 1% change in the independent variable (x); that is, $E = (\Delta y/y)/(\Delta x/x)$.

†Energy submodels are now being developed for gas and electric water heaters, gas and electric ranges, refrigerators, and freezers.

to 2000. Outputs from the simulator include 72 fuel use components (Q_t^{ikm}) for each year (4 fuels x 6 end uses x 3 housing types).* Each fuel use component is determined in the simulation as the product of five factors:

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

where HT is the stock of occupied housing units, C is the fraction (market share) of households with a particular type of equipment, TI is the thermal integrity of housing units (for space heating and air conditioning only), EU is the average annual energy use for the type of equipment, and U is a usage factor (see Fig. 4).

As an example, consider consumption of electricity for space heating in single-family homes. HT is the stock of occupied single-family homes and C is the fraction of single-family homes that use electricity for heating. TI is the average thermal integrity (scaled to 1970, TI_{1970} = 1.0) of single-family homes that use electricity for heating, EU is the average annual energy requirement (in J/unit) of an electric space heating system, and U is a usage factor (U_{1970} = 1.0) that reflects how intensely households use their electric heating systems.

Table 5 summarizes the inputs required to operate the simulation model, and Table 6 lists the outputs produced by the model.

*Many of these 72 cells are empty, for example, oil-fired refrigerators.

Table 5. Inputs to residential energy use model

Parameters
Price and income elasticities, lag values
Housing choice matrix
Initial conditions
1970 Housing stock
1970 Equipment saturations
1970 Equipment fuel uses, aggregate fuel use
1970 Fuel prices
1969/1970 Ratios of saturations and usage
Boundary conditions (1970-2000)
Population, headship rates
Fuel prices (electricity, gas, oil)
Incomes
New equipment energy use
Thermal integrity of residential buildings

Table 6. Outputs from residential energy use model: 1970-2000

Housing stock, retirements, new construction
Equipment saturations by fuel for each end-use
Average equipment energy use
Average thermal integrity of housing stock
Usage factors
Residential fuel use
fuel
end-use
housing type
Expenditures on fuels

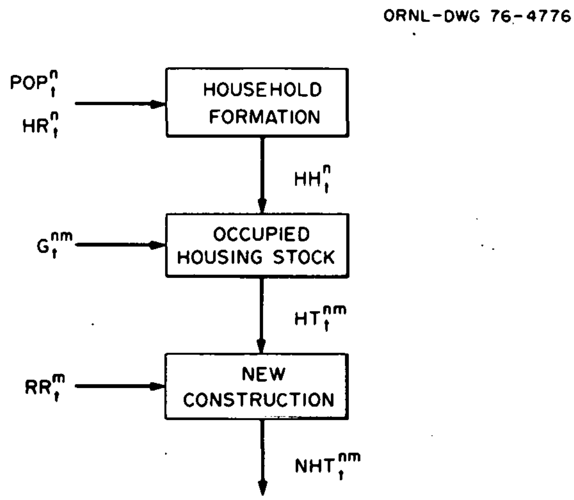
2.1 HOUSING SUBMODEL

To a large extent, the demand for household fuels is fixed once the decision to form a household is made and the type of housing unit is selected. Thus it is important to choose a model sensitive to important demographic and economic determinants to forecast household formation and housing selection.

Unfortunately, our search of housing literature[15-21] failed to yield a single model that satisfied all our needs. Most of the models of housing demand are short-run in nature, deal with only a small portion of the national housing market, or both. We needed a model that would produce forecasts of housing demand for the nation, by type of structure, over a long period (to 2000).

We found five forecasts of aggregate national housing demand that dealt with a reasonable fraction of the time period we are concerned with. However, four of these models[17,18,21,22] provided no explicit methodology to produce the forecasts. Thus we could neither replicate their forecasts nor produce alternatives based on different assumptions about population, income, and housing prices.

The model developed for the U.S. Forest Service[15] had most of the characteristics we needed. Their model (Fig. 5) estimates stock of occupied housing units year by year. In addition, estimates of new construction for single-family units, apartments, and mobile homes are produced each year of the simulation, disaggregated by source of demand — household formation and replacement of existing stock. The input data required to run the housing model include:



POP	POPULATION	n	AGE GROUP
HH	HOUSEHOLDS	m	HOUSING TYPE
HR	HEADSHIP RATE, HH_t^n/POP_t^n	t	YEAR
G	HOUSING TYPE OCCUPANCY RATE		
HT	OCCUPIED HOUSING STOCK		
RR	REPLACEMENT RATE		
NHT	NEW CONSTRUCTION OF OCCUPIED HOUSING UNITS		

Fig. 5. Schematic of housing model.

1. population and headship rates by year and age class,*
2. replacement rates by type of housing unit, and
3. housing occupancy by type of unit and age of head for 1970 and 2000.

The model calculates the number of households by age of head each year as the product of population and headship rate. This produces an estimate of the total stock of occupied housing units each year (identically equal to the number of households). Next, occupied housing units are shared among the three housing types according to the occupancy matrix.† Finally,

*Headship rate is defined as households in age group i/total population in age group i.

†Housing choices for each age class are obtained from a linear interpolation of the 1970 and 2000 housing occupancy matrices.

construction of new occupied housing units is calculated each year from household formation and retirement of existing stock.

The structure and operation of this model are simple. Over time, housing demand and new construction are essentially predetermined by the input conditions; that is, the model contains no behavioral characteristics. However, we plan to improve the model. We will retain the structure of the Forest Service model but convert the more important relationships in the model from a deterministic form to a behavioral specification.

We replaced much of the input data originally used in the model with recent data from the Bureau of the Census. We are currently using population and household forecasts from ref. 23. Initial conditions on housing stock and occupancy rates for 1970 were obtained from the 1970 Public Use Sample tape.[10] Data for the period 1970 to 1975 on households and housing type were obtained from Census publications Series P-20, the 1970 Census of Housing,[10] and the 1973 Annual Housing Survey.[11] Thus, although the model we are presently using is only slightly different from the original model, the input data are significantly revised.*

Figure 6 shows the alternative housing forecasts used with the residential energy use simulator. The forecasts were prepared using the Census series A and C household forecasts[23] and two different assumptions for the housing choice matrix for 2000. The first assumes no change from 1970 (i.e., housing choice as a function of age is identical to that of 1970),

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*Copies of the input data on headship rates, housing choice, and replacement rates, and the consequent forecasts produced by the housing model are available from the authors.

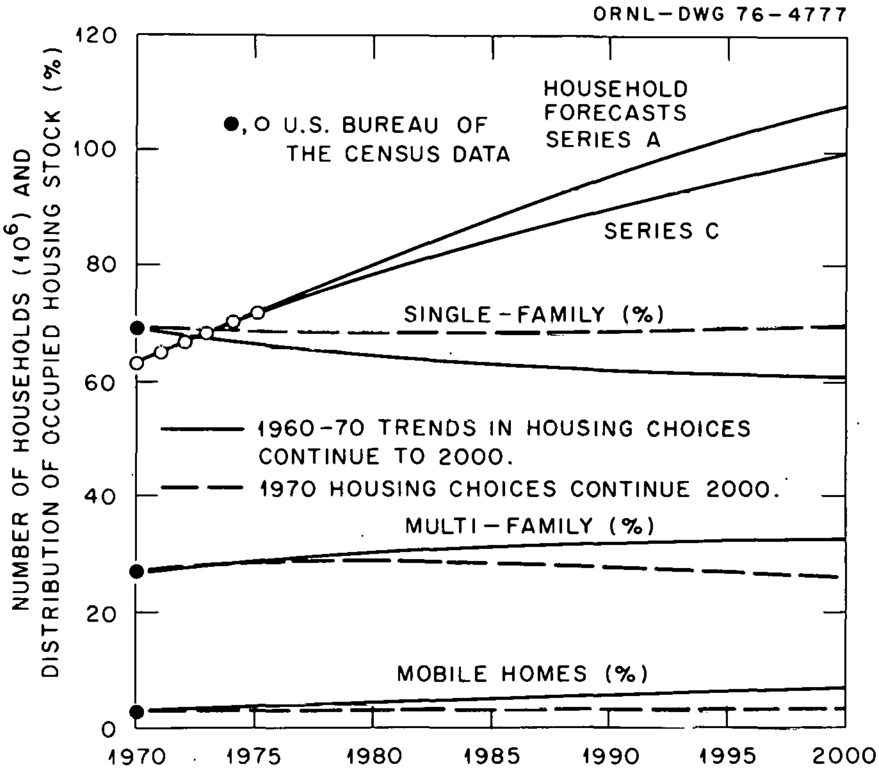

Fig. 6. Forecasts of households and occupied housing stock: 1970-2000.

and the second assumes a linear extrapolation of the 1960 to 1970 trends in housing choice by age of household head.[10] The two household forecasts differ by 8% in 2000. Continuation of the 1960 to 1970 trends in housing choices yields higher stocks of mobile homes and apartments in 2000 (and lower stocks of single-family units) than would a continuation of the 1970 age-dependent housing choice.

We compared forecasts from our modified Forest Service model with the MIT-Harvard[18] results for 1980, the National Association of Home Builders (NAHB)[21] results for 1980 and 1990, and the A. D. Little (ADL)[22] results for 1980 and 1990. Agreement among the various estimates of households, housing choice, and new construction is excellent.

2.2 ELASTICITY ESTIMATOR

This portion of the model calculates, in response to changes in fuel prices and incomes, the economic behavior of households with respect to fuel uses (Fig. 7). The driving force of the estimator is a set of overall price and income elasticities for energy demands in the combined household/commercial sector. No models yet exist that treat the household sector separately, because the Bureau of Mines[4] aggregates the household and commercial sectors. Estimates of price elasticities for electricity, gas, and oil, and income elasticities were obtained from refs. 24-26.

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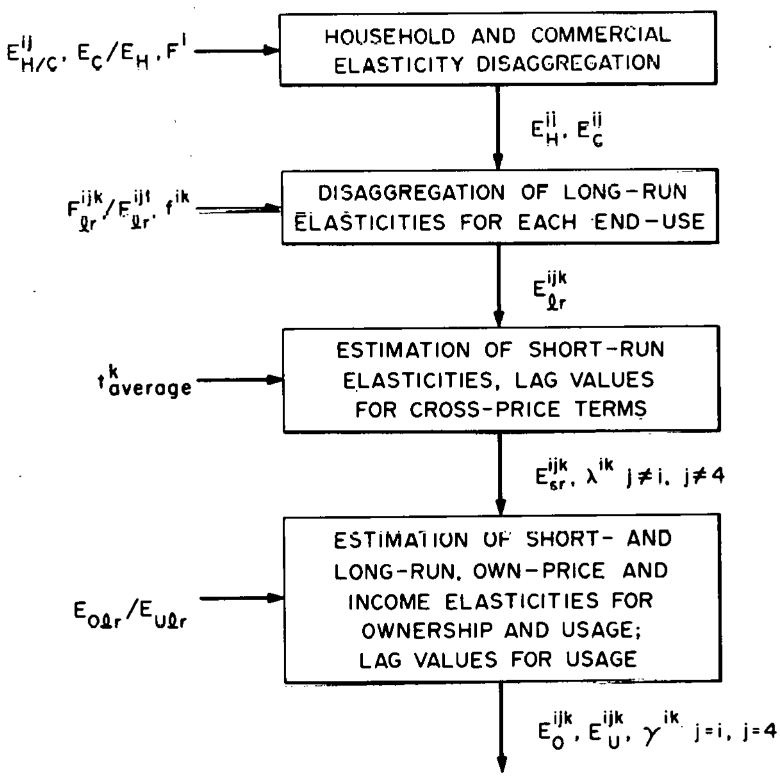

Fig. 7. Schematic of elasticity estimator.

To estimate elasticities for the household sector alone, one must obtain values of the ratios of commercial/household elasticities (E_C/E_H) and the fraction of each fuel type consumed in the household sector (F^i). Because individual models of energy demand for each sector do not exist, we had only the ORNL electricity demand models[27] to rely on for the former set of parameters. Based on these results, we selected a value of $E_C/E_H = 1.5$. This implies that residential demands for fuels are only two-thirds as responsive to price and income changes as are commercial demands.* Values for the fractions of each fuel consumed in the household sector were obtained from refs. 1-5. Combining these data and estimates yields the overall household price and income elasticities shown in Table 7 and calculated as:

$$E_H^{ij} = \frac{E_{H/C}^{ij}}{F^i + (1 - F^i)\ (E_C/E_H)} ,$$

where E_H^{ij} is the elasticity of household demand for fuel i with respect to fuel price j (or income for $j = 4$), F^i is the fraction of household/commercial use of fuel i in the household sector, and E_C/E_H is the assumed ratio of commercial to household elasticities.

The elasticity estimator derives elasticity values for each end use. Three recent cross-sectional studies[28-30] analyzed equipment market shares by fuel for space heating, water heating, cooking, and air

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*The values of household elasticities are rather insensitive to the assumption on commercial/household elasticity ratio, because the household fractions (F^i) — 0.61, 0.78, and 0.54 — for electricity, gas, and oil respectively are larger than the commercial sector fractions. Thus the ratio assumed for E_C/E_H affects primarily the derived values of commercial sector elasticities.

Table 7. Price and income elasticities for household fuel uses[a]

	Price of:			
	Electricity	Gas	Oil	Income
Electricity				
sr	−0.16	0.01		0.10
lr	−0.84	0.14	0.04	0.52
Gas				
sr	0.01	−0.14		0.08
lr	0.15	−0.91	0.05	0.56
Oil				
sr		0.01	−0.15	0.08
lr	0.13	0.15	−0.91	0.50

[a]sr = short run, lr = long run.

conditioning. We compared own- and cross-price elasticities of equipment ownership from these three studies in terms of their relationship to comparable values for space heating. Evidence from these studies on income elasticities for each end use was meagre and difficult to interpret. Therefore we assumed the same income elasticity for each fuel and each end use.

The assumed elasticity ratios for each end use were combined, by fuel type and end use (see Sect. 1 and ref. 13) with data on fuel consumption to derive long-run elasticities for each end use, as follows:

$$E^{ij1}_{lr} = \frac{E^{ij}_{H}}{f^{i1} + \sum_{k=2}^{6} f^{ik} \, (E^{ijk}/E^{ij1})} ,$$

$$E^{ijk}_{lr} = (E^{ijk}/E^{ij1}) \, E^{ij1}_{lr} ,$$

where E_{lr}^{ijk} is the long-run elasticity of household demand for fuel i with respect to fuel price j (or income for $j = 4$) for end use k, f^{ik} is the fraction of household use of fuel i for end use k, and E^{ijk}/E^{ij1} is the ratio of elasticity for end use k to the comparable elasticity for space heating ($k = 1$).

These long-run elasticities are disaggregated into two components for ownership and usage; that is, $E = E_o + E_u$. The usage elasticity E_u is, by definition, equal to zero for all cross-price terms. Based on results from ref. 28, we constrained the two long-run elasticities, relative to each other, to $E_o/E_u = 2$. Thus we assumed that 67% of the long-run response to a change in own-price or income is due to changes in equipment ownership and 33% is due to changes in equipment usage.* Then:

$$E_{olr}^{ijk} = \frac{2}{3} \cdot E_{lr}^{ijk} \quad \text{and} \quad E_{ulr}^{ijk} = \frac{1}{3} \cdot E_{lr}^{ijk} \quad .$$

The program next calculates short-run (one-year) elasticities for the two cross-price terms (those for which $E_u = 0$). We assume that the basic determinant of equipment ownership dynamics is equipment lifetime. Based on estimates in refs. 13, 31, and 32, we assumed the following average lifetimes (t_{average}) for each end use equipment type:

*In the short run, E_o/E_u is less than 2; that is, usage changes are relatively more important in the short run (see Fig. 8).

k	End use	$t_{average}$ (years)
1	Space heating	15
2	Water heating	7
3	Refrigeration	14
4	Cooking	13
5	Air conditioning	9
6	Other	10

Using these average lifetimes, the short-run cross-price elasticities are defined by:

$$E_{osr}^{ijk} = E_{lr}^{ijk}\left[1 - \frac{1}{2^{1/t_{average}}}\right] .$$

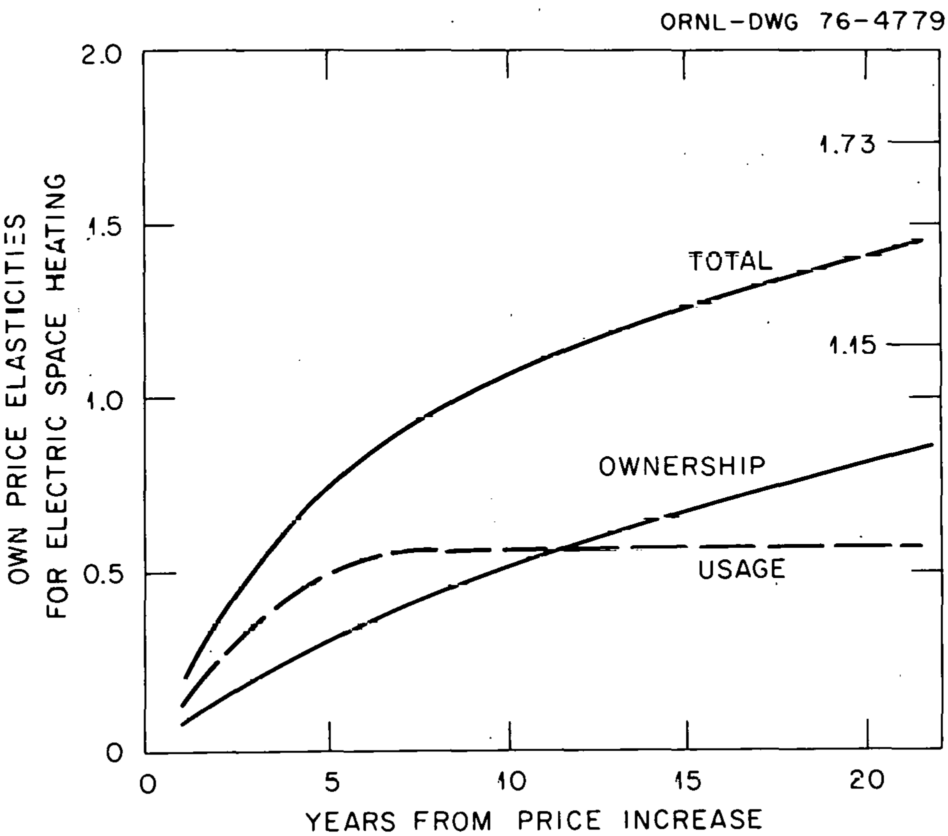

Fig. 8. Effects of a price change in electricity on ownership and usage of electric space heating equipment.

Finally, the program calculates short-run elasticities for the own-price and income terms. The short-run ownership elasticity is calculated using the formula previously given. The short-run usage elasticity is calculated as the difference between the overall (ownership plus usage) short-run elasticity and the ownership short-run elasticity, as follows:

$$E^{ijk}_{usr} = E^{ijk}_{sr} - E^{ijk}_{osr} \quad , \qquad \text{for } j = i \text{ and } j = 4 \quad ,$$

where E^{ijk}_{sr} is determined so as to satisfy

$$E^{ij}_{sr} = \sum_{k=1}^{6} f^{ik} \cdot E^{ijk}_{sr} \quad .$$

In summary, the elasticity estimator derives a set of 144 price and income elasticities and 36 lag values that define the ratios of short-run to long-run elasticities.*

Figure 8 illustrates the dynamics of energy use in response to a change in electricity price for electric space heating. The curves show changes in usage and ownership, and the combined change due to a step change in electricity price in year 1. The usage response is quite rapid: in less than two years the response reaches more than 50% of its equilibrium value. However, the response is much slower for equipment ownership: it takes 11 years to reach 50% of the equilibrium value. Combining these two curves yields a 50% response in six years. Twenty years after the electricity price change, 80% of the adjustment is complete. (The

*One can readily change the inputs to the elasticity estimator computer program and then generate a new set of elasticities and lag values for input to the energy use simulator. Copies of the input data and estimates, and calculated elasticities and lag values are available from the authors.

differences between ownership and usage response are most pronounced for space heating because of the long average lifetime for heating equipment. For other end uses, the response times are less.)

2.3 ENERGY USE SIMULATOR

The overall simulation program combines outputs from the housing model, elasticity estimator, and engineering cost submodel (energy efficiencies for residential structures and new equipment by end use, fuel, and year) to simulate energy use patterns in the household sector from 1970 to 2000.

The basic equation used to define residential use of fuel i for end use k in housing type m for year t is:

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

(See page 12 for definitions of these terms.)

The stocks of occupied housing units are obtained as outputs from the housing model. The market share and usage terms, C and U, are determined by equations of the form:

$$\ln Y_t^{ikm} = \sum_{j=1}^{3} \left[E^{ijk} \cdot \ln\left(X_{jt} \cdot TI_t^{jkm} \cdot EU_t^{jkm} \right) \right] + E^{i4k} \cdot \ln X_{4t}$$

$$+ L^{ik} \cdot \ln Y_{t-1}^{ikm} + \text{constant}^{ikm} \quad .$$

The Y's are the dependent variables (either C or U) and the X's are the independent variables (fuel prices and per capita income). The coefficients, E and L, are from the elasticity estimator.* The constants are set so that the equations predict correct values of C and U for 1970.

Note that the price elasticities are multiplied by the natural logarithm of the product of fuel price, average equipment energy use, and average structural thermal integrity (for space heating and air conditioning). Thus we hypothesize that consumers respond not to fuel prices alone but to annual operating costs. This formulation provides a strong link between technological changes (in *EU* and/or *TI*) and economic changes (fuel prices). For example, if *EU* for gas water heating is reduced because of increased jacket insulation, the above equations will predict increases in gas water heater ownership (at the expense of electric and oil water heater ownership) and in gas-heated hot water usage (e.g., people will take longer showers), because the cost of operating a gas water heater has been reduced. Thus part of the gas savings one would predict from increased technical efficiency is lost because of fuel switching (which saves other fuels) and behavioral changes in usage patterns.

The *EU* terms for each type of equipment are calculated based on the NEU (new equipment energy use values) input to the model, average

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*The simulation program reads those coefficients as inputs. Therefore alternative elasticity and lag values from other runs of the elasticity estimator or other sources can be input to the simulation model.

lifetimes, and existing stocks.* Thus the *EU* values represent the average energy use of all equipment of that type in use during year *t* (including new units sold that year and units remaining from the previous year).

The *TI* terms (which apply only to space heating and air conditioning) are derived in a similar manner. However, *TI* for the housing stock can change in two ways in the model: for new housing units and for existing housing units (retrofit). The simulator keeps track of new housing construction, removals of past housing stocks, and the appropriate *TI* values for each fuel, end use, and housing type.

Household use of "other" fuels (coal, coke, LP gas, and wood) is specified as a residual based on 1970 saturations and fuel use estimates for these fuels. Equipment saturations for the combination of "other and none" are assumed to decay exponentially over time at a rate based on the 1960 to 1970 and 1970 to 1973 decays.[10,11] Equipment energy use and thermal integrity values for other/none are held constant at their 1970 values. Thus the simulator estimates a declining fraction of total household fuel use accounted for by other fuels. This simplified specification of other fuel use is unlikely to cause significant forecasting

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*The three housing types considered have different thermal requirements (at the structure boundary) because of differences in size, geometry, and construction quality. We assigned the following relative values for space heating and air conditioning *EU* for 1970, based on the unit sizes shown below:

	$\frac{EU}{EU_{SF}}$	Size (ft^2)	Size (m^2)
Single family	1.00	1500	139
Multifamily	0.41	1000	93
Trailer	0.61	720	67

errors, because these fuels account for only a small and declining fraction of total residential fuel use — down from 10% in 1960 to 6% in 1970 and 5% in 1974.[1-5]

Initial conditions (Table 5) required to run the simulator include values for equipment saturation by fuel, end use, and housing type for 1970 and the corresponding 1969/1970 ratios. The 1970 values were determined by performing cross-classifications with the 1970 Public Use Sample tape.[10] The 1969/1970 ratios were obtained from the 1960, 1970, and 1973 saturations by fuel and end use.

Initial values of *EU* for 1970 were obtained from ref. 13, scaled up to match control totals for residential uses of electricity, gas, oil, and other fuels from refs. 1-5.

Values of *U* for 1970 are set equal to 1.0 by definition. The ratios of 1969/1970 usage factors for each fuel were obtained by comparing 1969 and 1970 residential fuel uses and assumed equipment saturations.

Boundary conditions from 1970 to 2000 required to run the model (see Table 5) include population, headship rates, fuel prices, incomes, new equipment energy use (by fuel, end use, and housing type), thermal integrity for new structures (by fuel and housing type), and thermal integrity for buildings constructed during or earlier than a specified year t_o, the standards to be implemented in year $t_1 > t_o$ (by fuel and housing type). Changing boundary conditions allows the user to simulate energy use over this 30-year period under various conditions. This can be used to test the energy and energy expenditure impacts of changes in demographic, economic, technological, and regulatory conditions.

3. VALIDATING THE MODEL

Before using the model to evaluate the energy impacts of alternative conservation strategies, we examine the performance of the model relative to historical data. Due to its ad hoc nature, we cannot apply the tests of statistical significance generally used to validate econometric models. Instead, we compare the model's abilities to predict energy use (aggregate, by fuel, and by end use) for the period 1960 through 1974. This comparison is performed twice: with the model started in 1960 and with the model started in 1970. The model is started with detailed data on residential fuel uses (by fuel and end use) for the initial year.

In addition, 24 ratios of equipment saturations for 1959/1960 (or 1969/1970) are required as input (4 fuels x 6 end uses); also three ratios of usage factors are required (electricity, gas, and oil). Data do not exist to specify a priori these 27 parameters. The 24 equipment saturation ratios are initially set by examining the 1950, 1960, 1970, and 1973 saturation data.[10-12]

However, because these data span several years (not the adjacent years required as input to the model), these 24 ratios are adjusted so that the model predicts saturations at the next census year with reasonable accuracy.

Table 8 compares saturation data with predictions of the model started in 1960 and 1970. Because we adjust these 24 saturation ratio inputs, the model gives excellent results.

Table 8. Comparison of actual and predicted values of household equipment ownership saturation ratios

	1970/1960 ratios		1973/1970 ratios		
	Actual[a]	Model A[b]	Actual[a]	Model A[b]	Model B[b]
Space heating					
Electricity	4.28	4.17	1.35	1.34	1.36
Gas	1.28	1.27	1.01	1.03	1.00
Oil	0.80	0.81	0.96	0.92	0.95
Other/none	0.50	0.50	0.84	0.82	0.86
Water heating					
Electricity	1.25	1.25	1.12	1.06	1.09
Gas	1.16	1.16	0.99	1.02	1.00
Oil	0.84	0.85	0.94	0.92	0.97
Other/none	0.48	0.48	0.81	0.82	0.80
Cooking					
Electricity	1.32	1.31	1.10	1.05	1.09
Gas	0.96	0.96	0.94	0.99	0.94
Oil	0.45	0.55	0.20	0.90	1.00
Other/none	0.59	0.59	0.94	0.86	0.96
Air conditioning					
Electric	2.88	2.91	1.31	1.15	1.31
None	0.73	0.73	0.83	0.91	0.83

[a]Saturation data are from Table 3 (refs. 10-12).

[b]Model A refers to the baseline run from 1960-1990. Model B refers to the baseline run from 1970-2000.

The only real test of the model's performance is a comparison of the 1973/1970 ratios between data and outputs from the 1960 to 1990 run. The model does a good job of forecasting trends in equipment saturation. The 1960 simulation slightly underpredicts ownership of electrical equipment and overpredicts ownership of gas equipment, probably because of the natural gas shortage that first appeared around 1970. (Because the model developed here is a demand model, it assumes implicitly that energy supplies are always available at exogenously specified prices.)

The three usage ratios are set so that the model accurately predicts energy uses during the first two or three years of the simulation. Because of the dynamics of usage change (see Fig. 8), the impacts of changes in usage ratios disappear within five years after the start of a simulation. The impacts of saturation ratio selection, however, last for at least a decade.

Figure 9 compares actual residential fuel uses (electricity, gas, oil, and total) with the model's predictions from 1960 through 1974. The solid

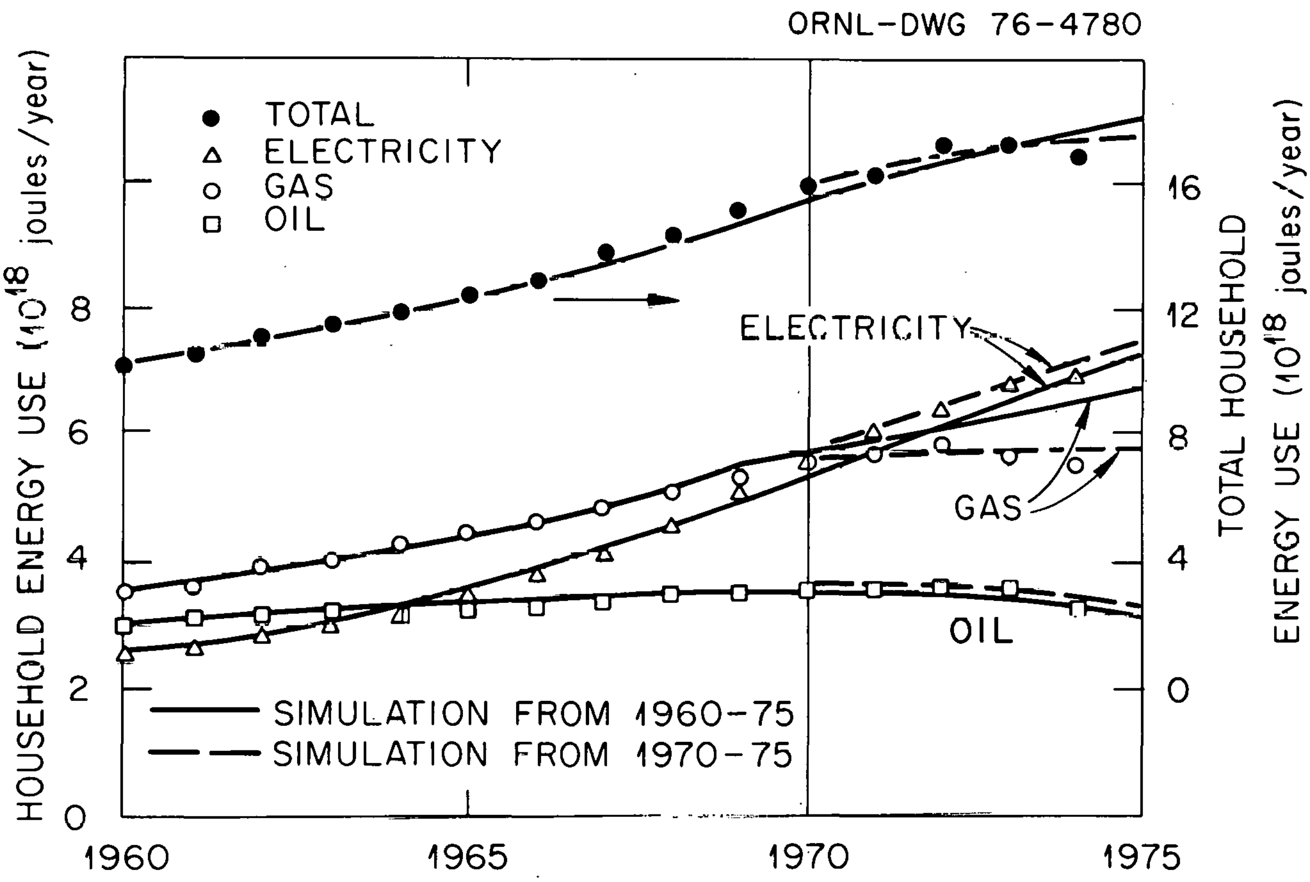

Fig. 9. Comparisons of residential energy use data from 1960-1974 with outputs from the model.

curves in Fig. 9 are from the 1960 to 1990 simulation, and the dashed curves are from the 1970 to 2000 simulation. The 1960 simulation does an excellent job of predicting trends for all three fuels up to 1970. However, it underpredicts electricity use and overpredicts natural gas use from 1970 to 1974.

Predictions with the 1970 simulation are more accurate than those with the 1960 simulation; the improvements are due to the 27 1969/1970 ratios input to the model. Because of these "degrees-of-freedom," the simulation started in 1970 does an excellent job of predicting actual residential fuel uses up to 1974.

Although the two simulations are started at different years with different initial conditions, their predictions for the period 1975 to 1990 are nearly identical. The only significant difference between the two simulations concerns gas use from 1970 to 1980: the 1960 simulation predicts a higher growth in gas use than does the 1970 simulation.

The 1960 simulation's end use distributions for 1970 and 1973 are compared with estimates from Table 4 in Table 9. (The 1970 simulation's 1973 end use distribution exactly matches the actual distribution.) The model slightly overpredicts energy use for space and water heating, and underpredicts electricity uses for refrigeration and other energy consumers. The refrigerator underprediction is caused by growth in average electricity consumption of refrigerators during the 1960s. This growth is due to the use of larger units and widespread adoption of the automatic defrost option. Underprediction of other electricity uses stems from the model's lack of disaggregation for electric dishwashers, clothes washers and dryers, televisions, and other small appliances.

Table 9. Comparison of actual and predicted household energy end-use distributions

	1970 (percent)		1973 (percent)	
	Simulation[a]	Actual	Simulation[a]	Actual
Space heating	58	56	57	55
Water heating	17	14	17	14
Refrigeration	6	8	6	8
Cooking	5	5	5	5
Air conditioning	4	4	5	6
Other	10	13	10	12
Total	100	100	100	100

[a]The simulation results are from the 1960–1990 baseline run.

The results presented here suggest that the residential energy use simulation provides excellent predictions of actual fuel use by fuel and end use from 1960 to 1974. This lends confidence to our use of the model (in the next section) to simulate future residential fuel use trends and patterns.

4. DEVELOPING A BASELINE

The purpose of a baseline energy use forecast is to provide a reference that can be used to compare simulations of different policies and technological changes. Developing the baseline involves selection of appropriate boundary conditions (to 2000) on: population, households, housing choice, fuel prices, incomes, efficiencies for new residential HVAC equipment and appliances, and thermal integrities for new and existing structures.

4.1 BOUNDARY CONDITIONS

The Bureau of the Census[23] developed three sets of household projections from 1975 to 1990. We extended their high and low forecasts to the year 2000 by fitting regression equations to their 1975 to 1990 age-dependent headship rate estimates (see Fig. 6 and Table 10). The Bureau's household forecasts are nearly independent of population forecasts, because almost all of the potential 1990 heads of households are already born; the range of populations[33] consistent with the household forecasts is also shown in Table 10.

We selected the low household forecast (series C) for the baseline because it agrees well with the ADL and NAHB household forecasts. However, we shall later evaluate the impacts on energy use of the series A forecast.

Table 10. Alternative forecasts of U.S. households and residential construction

	Resident population (10^6)	Households (10^6 units)		New construction[a] (10^6 units)	
		Low (C)	High (A)	Low	High
1970	204	63.4			
1975	213	71.5		2.2	2.5
1980	219–224	78.2	80.0	2.0	2.3
1985	227–240	84.7	88.5	1.9	2.4
1990	234–256	90.2	96.3	1.3	2.4
2000	244–285	100.3	108.5	1.8	2.2

[a]The construction figures given here account only for growth in households and replacement of scrapped occupied housing units; vacancy requirements are not included.

The housing model also requires, as input, a housing choice matrix for the year 2000. As shown in Fig. 6, we assumed that trends between 1960 and 1970 would continue to the year 2000; that is, we linearly extrapolated changes in housing choice by age of household head from 1960 through 1970 to the year 2000.

We reviewed fuel price forecasts developed in FEA's *Project Independence Report*,[34] their *National Energy Outlook*,[35] and those produced by Anderson's energy supply/demand/price model.[36] We selected two sets of Anderson's fuel price outputs to use with our model: a low price series (equivalent to a \$5/bbl crude oil price in 1972), and a pessimistic high price series of \$11/bbl (Table 11). We selected the low price series for the baseline. Later we will examine differences in fuel uses between the two.

Table 11. Assumed real fuel price and per-capita income trajectories to 2000[a]

	Electricity[b]		Gas[b]		Oil[b]		Income[c]	
	Low	High	Low	High	Low	High	Low	High
1970	1.00		1.00		1.00		1.00	
1975	1.09		1.17		1.49		1.06	
1980	1.17	1.29	1.22	1.44	1.26	2.02	1.14	1.29
1985	1.27	1.41	1.32	1.39	1.36	2.02	1.23	1.48
1990	1.41	1.57	1.43	1.55	1.47	2.02	1.32	1.71
2000	1.67	1.88	1.68	1.83	1.70	2.02	1.53	2.28

[a]The values shown here are normalized to 1970 data. Residential fuel prices in 1970 were (in 1970-dollars/GJ): electricity, 1.73; gas, 0.98; oil, 1.26. Per-capita income was $3970 in 1970.

[b]The high fuel price forecasts are based on the $11/bbl pessimistic scenario of ref. 36; the low fuel price forecasts are based on the $5/bbl scenario.

[c]In the high growth case, real per-capita income is assumed to grow at 2.9%/year; and at 1.5%/year in the low growth case.

Projections of per capita income are available from a number of large macroeconomic models, such as those developed by Data Resources, Chase Econometrics, and the Bureau of Economic Analysis (BEA). Annual growth rates in real per capita income range from a low of 1.5% to a high of 3.2%. We used the BEA forecast[37] (real growth of 2.9%/year) for the baseline. We also will simulate the energy consequences of a 1.5%/year growth (Table 11).

The final sets of boundary conditions required for the baseline include changes in unit energy requirements of new residential HVAC equipment and appliances and changes in thermal integrity of residential structures. Although these values are certain to decline over the next 25 years, we assume in the baseline run that there are no technical improvements in the design and production of new equipment and structures. Another run, discussed later, shows the energy impacts of improvements in equipment and structural efficiencies.

4.2 BASELINE FORECAST

Figure 10 summarizes results of the baseline run from 1970 to 2000, using the boundary conditions discussed above.* The model estimates that household fuel use will grow from 15.9 GGJ in 1970 to 17.6 GGJ in 1975, 19.5 GGJ in 1980, and 26.4 GGJ in 2000. The average annual growth rate from 1975 to 2000 is 1.7% (compared with 3.7% from 1950 to 1970 and 1.5% from 1970 to 1974. Energy use per household during this 25-year period is projected to grow at 0.3% annually (compared with 1.7% from 1950 to 1970 and -1.0% between 1970 and 1974).

Thus household fuel use is projected to grow more slowly than it did during the past 25 years but more rapidly than during the past few years. The growth in energy use forecast to the year 2000 is slower than the 1950 to 1970 historical trend because of higher and rising fuel prices and slower growth in household formation assumed for the forecast period.

Figure 11 shows changes in the distribution of fuels from 1970 to 2000. Electricity consumption grows at 2.7% annually, while gas and oil grow at only 1.0 and 0.5% annually. Thus the percentage of total household fuel provided by electricity grows from 35% in 1970 to 56% in 2000. The percentages provided by all other fuels decline over time.

*An annotated listing of the computer output for the baseline run is available from the authors.

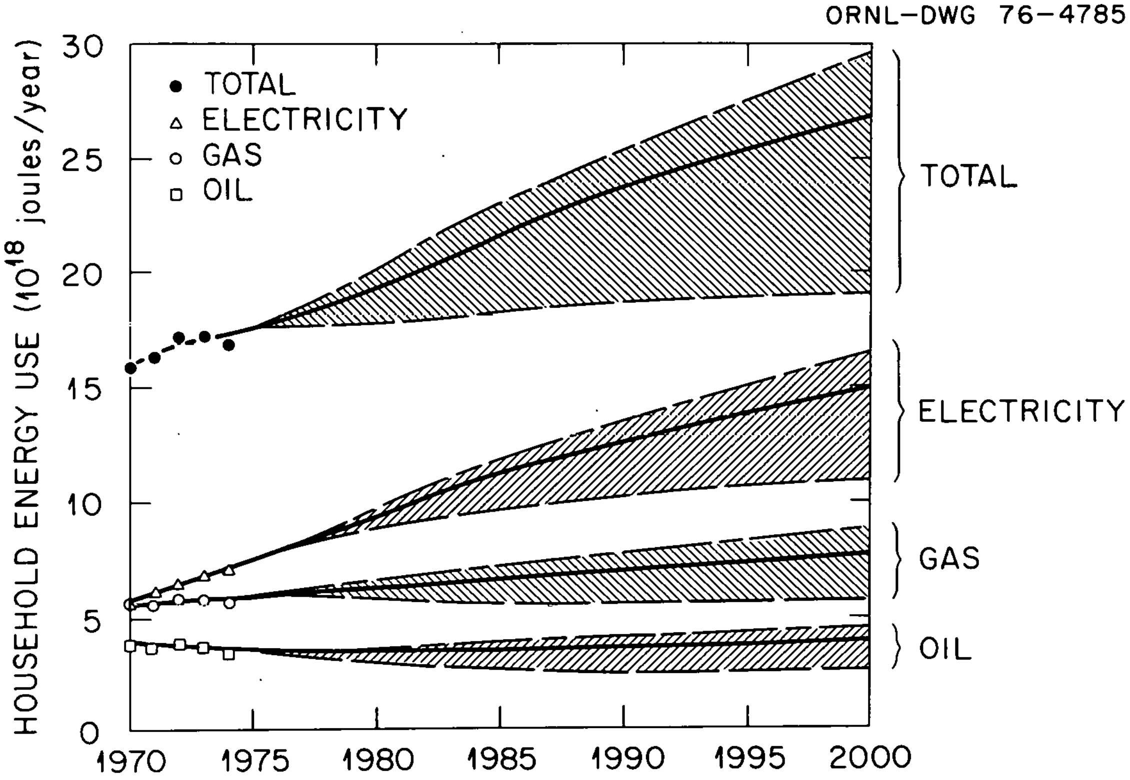

Fig. 10. High, baseline, and low forecasts of household fuel use.

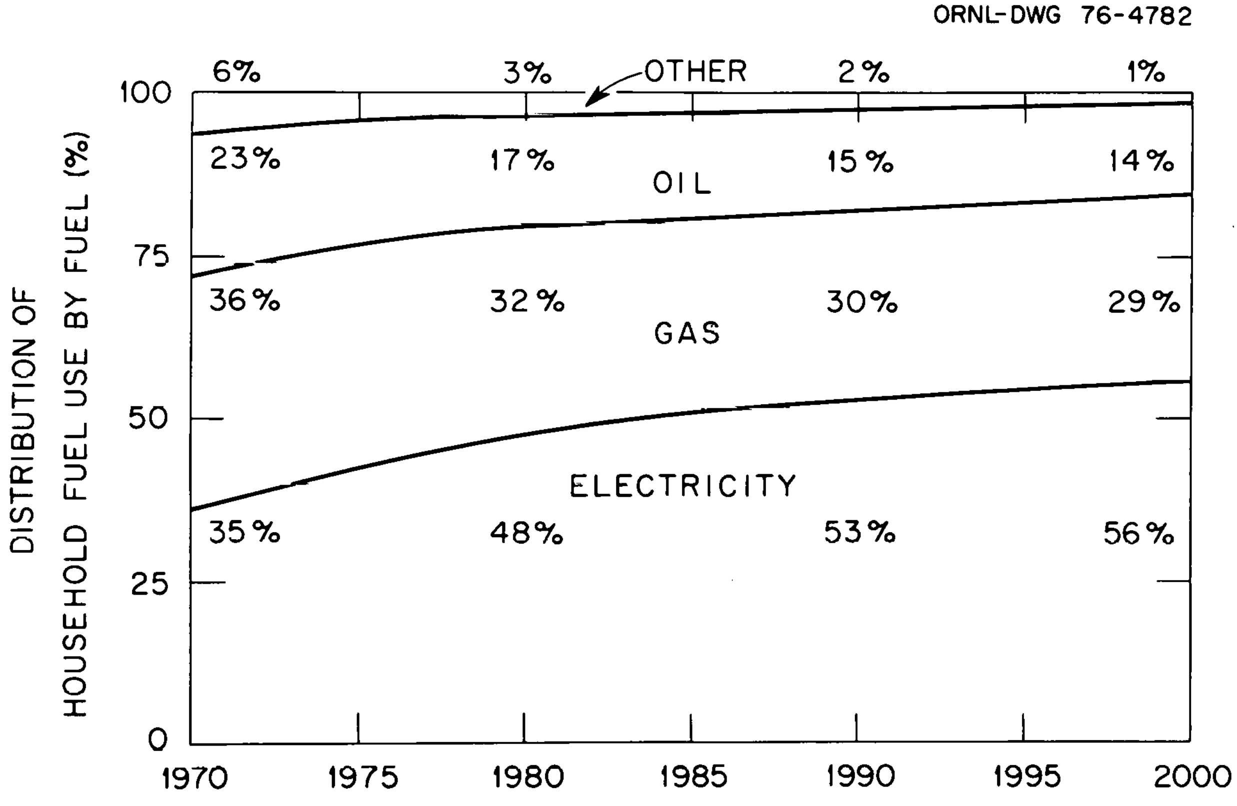

Fig. 11. Baseline forecast distribution of household fuel use by fuel.

The distribution of fuel use by housing type changes slightly during this period. The percentage consumed in single-family units declines from 78% in 1970 to 71% in 2000. The percentages consumed in multifamily units and trailers increase from 19% and 3% respectively in 1970 to 23% and 6% in 2000.

The distribution of household fuel by end use also changes over time (Fig. 12). Space heating (the largest end use during the entire 30-year period) declines from 56% to 49% of the total. Air conditioning, on the other hand, increases its share of the total from 4% to 11%. Other end uses remain fairly constant as percentages of the total.

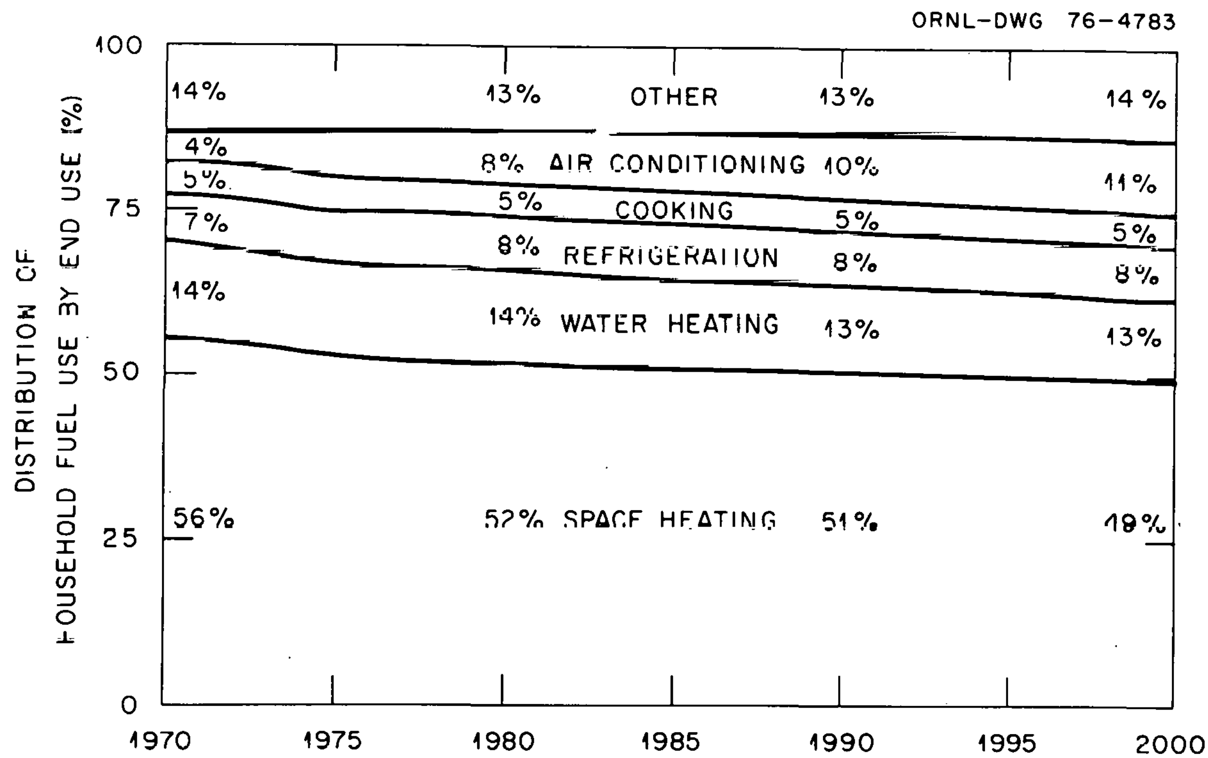

Fig. 12. Baseline forecast distribution of household fuel by end use.

Figure 13 shows the baseline forecast of residential fuel expenditures (in terms of constant 1970 dollars). Total expenditures grow from $21 billion in 1970 to $29 billion in 1975 and $65 billion in 2000. The annual growth rate in household fuel expenditures averages 3.3% between 1975 and 2000, less than the 3.8% average annual growth in total personal income. Thus the impact of rising incomes more than offsets the impact of rising fuel prices on overall household fuel expenditures.

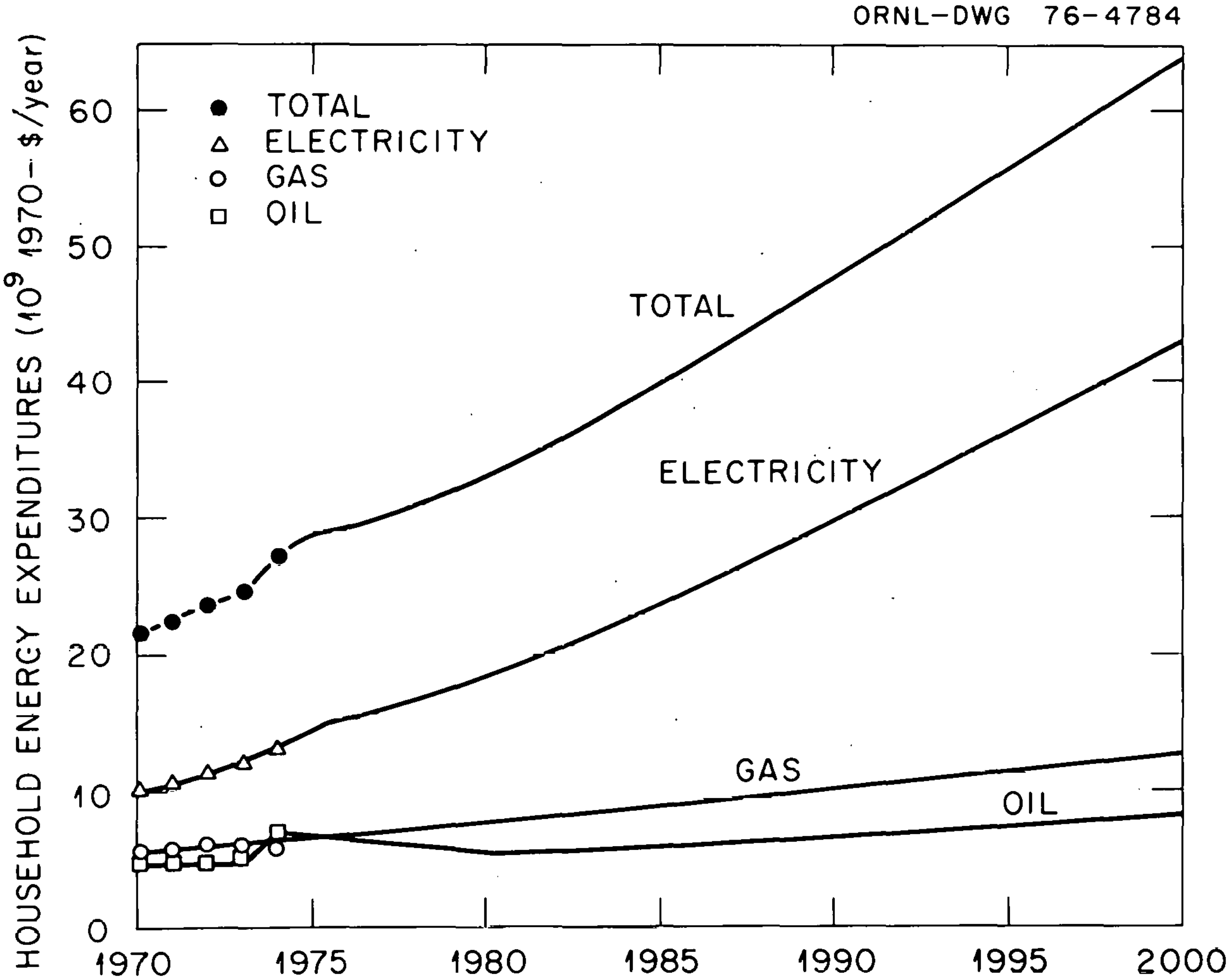

Fig. 13. Baseline forecast of household energy expenditures.

4.3 COMPARISON WITH OTHER FORECASTS

As a check on the "reasonableness" of our baseline results, we compare the outputs from our baseline run with forecasts developed by FEA,[35] ADL,[22] Dole,[13] and Westinghouse[38] (see Table 12). Because these forecasts were prepared using different reference years and definitions, we compare the forecasts in terms of annual growth rates rather than absolute energy values. Our forecast of overall growth in fuel use is lower than those prepared by FEA (to 1985), Westinghouse (to 2000), and ADL (to 1990). Our forecast is higher than Dole's (to 2000). Differences among the forecasts are small, especially in light of the different procedures and assumptions used to forecast fuel use.

Table 12. Alternative forecasts of household fuel use

Source[a]	Years	Average annual growth rate, percent			
		Electricity	Gas	Oil	Total
FEA	1974–1985	7.5	−1.8	3.4	4.3
ORNL		3.9	1.0	0.2	2.1
ADL	1970–1990	4.7	1.5	1.0	2.4
ORNL		4.0	1.0	−0.2	1.9
Dole	1970–2000	2.9	0	−0.9	1.2
ORNL		3.2	1.0	0	1.7
Westinghouse	1975–2000	3.8	0.4	−0.8	2.0
ORNL		2.7	1.0	0.5	1.7

[a]These forecasts are from: FEA, ref. 35; ADL, ref. 22; Dole, ref. 13; and Westinghouse, ref. 38.

However, agreement among the forecasts concerning individual fuels is not as good as for aggregate fuel use. The ADL, FEA, and Westinghouse forecasts yield higher growth for electricity than does our model; only the Dole forecast yields a lower electricity growth than ours. Our forecast of growth in gas use is higher than those of Dole, FEA, and Westinghouse; and our forecast of growth in oil use is higher than those of Dole and Westinghouse.

Part of the variation among forecasts is due to different boundary conditions. For example, the FEA forecast assumes a lower growth in electricity prices and much higher growth in gas and oil prices than does our baseline. This helps explain the higher FEA forecast of electricity demand and the lower forecast of gas (but not oil) demand than those produced with our baseline. Similar comparisons can be made with the other forecasts.

The ADL and Westinghouse forecasts are based primarily on historical data and judgments concerning future trends in detailed determinants of household fuel use (housing stocks, equipment stocks, equipment efficiencies). However, neither of these models is explicitly sensitive to economic determinants of household fuel use; thus the impacts of alternative forecasts of fuel prices and incomes on household fuel use can only be evaluated judgmentally with these two forecasts.

The FEA forecast is based on a pure econometric model, sensitive only to fuel prices and incomes. It contains no information on stocks of equipment and structures and their energy efficiencies. Thus the FEA model cannot explicitly analyze changes in the engineering performance of household equipment over time.

Finally, Dole's forecast is based on an ad hoc combination of engineering judgment and sensitivity to fuel prices. Dole's forecast is based on the high fuel price series of ref. 36, which partly explains the lower fuel use forecast.

4.4 ALTERNATIVE FORECASTS

A forthcoming ORNL report will present detailed analyses of several energy conservation policies and programs and their impacts on residential fuel use and expenditures to 2000. For this report, we present only two alternative forecasts. The "high" forecast uses the same boundary conditions as does the baseline, except that household growth is assumed to increase according to the census series A forecast (see Table 10). Also, the high forecast assumes that the housing choice matrix remains unchanged from its 1970 values (Fig. 6). Thus the fraction of households occupying single-family structures is greater in the high forecast than in the baseline.

The "low" forecast uses the same inputs on household formation and housing choice as the baseline does. However, it assumes that per capita income grows at only 1.5%/year from 1975 to 2000 and that fuel prices grow more rapidly than in the baseline (see Table 11). The low forecast also assumes that unit energy requirements for all new equipment decrease over time. The schedule chosen roughly approximates the 1975 Department of Commerce voluntary targets[39] for 1980 with continued, but slower, improvements from 1980 to 2000 (see Table 13). Thermal integrity of all new structures is assumed to improve as shown in Table 13, roughly

Table 13. Assumed improvements in energy requirements for new equipment and thermal integrity for new structures (1970 = 1.0)

	1975	1980	1990	2000
Space heating equipment				
Electric	1.0	0.90	0.85	0.80
Gas	1.0	0.75	0.65	0.55
Oil	1.0	0.75	0.65	0.55
Water heating equipment				
Electric	1.0	0.90	0.86	0.82
Gas	1.0	0.75	0.65	0.55
Oil	1.0	0.85	0.79	0.73
Refrigerators	1.0	0.70	0.58	0.46
Cooking equipment				
Electric	1.0	0.90	0.86	0.82
Gas	1.0	0.70	0.58	0.46
Air conditioning equipment	1.0	0.80	0.72	0.64
Other equipment	1.0	0.90	0.86	0.82
Single-family units				
Space heating	1.0	0.84	0.84	0.84
Air conditioning	1.0	0.95	0.95	0.95
Apartments				
Space heating	1.0	0.54	0.54	0.54
Air conditioning	1.0	0.85	0.85	0.85
Trailers				
Space heating	1.0	0.84	0.84	0.84
Air conditioning	1.0	0.95	0.95	0.95

corresponding to implementation of the ASHRAE 90-75 standards[40] in 1980. Finally, retrofit standards are assumed to start in 1976, applied to all single- and multi-family housing units constructed before 1973; 10% of the single-family and 5% of the multifamily units still in use and not yet retrofitted are affected by the standards each year. The standards are set at half their values for new construction. No retrofit standards are applied to mobile homes because of their short lifetime.

Major outputs from the high, baseline, and low forecasts are shown in Table 14 and Fig. 10. Growth in total household fuel is positive in all three forecasts; however per household fuel use declines in the low forecast by about 1% annually. The high forecast of 29 GGJ in 2000 is 11 GGJ (58%) higher than the low forecast for that year. Thus the range of forecasts due to different boundary conditions is considerable. Cumulative fuel use between 1975 and 2000 is 603 GGJ in the high case and 456 GGJ in the low case; thus the high forecast requires 32% more fuel (in aggregate) between now and 2000 than does the low forecast. In the high forecast, household fuel expenditures reach $72 billion (1970-dollars) in 2000, almost 40% more than the $52 billion in the low forecast. Differences among forecasts in distribution by fuel and by end use are insignificant.

Table 14. Comparison of high, baseline, and low household fuel use forecasts

	Average annual growth rate, percent				
	Electricity	Gas	Oil	Total	Total per household
High	3.1	1.5	0.9	2.1	0.4
Baseline	2.7	1.0	0.5	1.7	0.3
Low	1.4	-0.4	-1.4	0.3	-1.1

Figure 10 shows that high growth in personal income, rapid household growth, continued patterns of household choice that favor single-family units, and no improvements in either technical efficiency of household equipment or thermal integrity of residential structures are likely to yield a growth in total household fuel use of at least 2%/year; thus, household fuel use in 2000, under these assumptions, will be approximately two-thirds greater than 1975 fuel use.

Slower growth in personal income, higher increases in fuel prices, slower household growth, continuation of the 1960 to 1970 trends in housing choice (shifts to apartments and trailers), significant improvements in technical efficiencies of household equipment, and improvements in thermal integrity of both new and existing structures are likely to yield only a slight growth in total household fuel use (and a decline in per household fuel use); under these assumptions, fuel use in 2000 might be no more than 10% above 1975 household fuel use.

5. SUMMARY AND CONCLUSIONS

The model developed here provides detailed forecasts of national annual energy use in the household sector for four fuels, six end uses, and three housing types. To calculate each of these fuel use components, the model computes stocks of occupied housing units (and new construction) by type, equipment market shares by fuel for each end use, average thermal integrity of occupied housing stocks, average unit energy requirements by type of equipment, and usage factors that reflect household behavior. Thus the model is sensitive to the major demographic, economic, and technological determinants of household fuel use. Comparisons of the model's outputs with historical data from 1960 to 1974 and with other forecasts to 2000 suggest that the model performs well.

The baseline forecast developed here shows aggregate household fuel use growing from 17.6 GGJ in 1975 to 26.4 GGJ in 2000, with an average annual growth rate of 1.7%. Demand for electricity grows at 2.7%/year during this period, while demands for gas and oil grow at only 1.0% and 0.5%/year respectively. Fuel expenditures grow from $29 billion in 1975 to $65 billion in 2000 (in 1970 dollars), with an average annual growth rate of 3.3%. The high forecast shows fuel use growing at an average annual rate of 2.1%, while the low forecast shows a growth of only 0.3% annually. This dramatic difference in fuel use — 29 and 18 GGJ in the year 2000 — is due to the differences in the assumed boundary conditions regarding household growth, housing choice, fuel prices, incomes, equipment efficiencies, and structural integrities.

Although the present model will probably be useful in evaluating energy and expenditure impacts of a variety of conservation policies and programs, it has several limitations that need to be considered (and that we hope to overcome with future work). These limitations are:

1. The housing model is insensitive to several important economic and demographic determinants of household formation and housing choice. The relationships that determine household formation and housing choice in the model depend only on the age of household head. Household income, household size, and prices of different housing types are not included in the model. We are presently working with the U.S. Forest Service to remedy these defects.

2. The price and income elasticities used here were developed using an ad hoc procedure. Because of this, we are unable to test the statistical significance of the coefficients and the relationships they represent. Our choice of the structural determination of equipment ownership (market shares) and usage is largely conjectural, because detailed data required to develop statistically rigorous models do not exist. Thus our hypotheses concerning relationships between equipment choice and household usage of that equipment and between fuel price and energy requirements (i.e., sensitivity to annual operating cost rather than to fuel price) should be considered plausible but unproven.

3. The market-share equations are sensitive to incomes and annual operating costs in the present model, but not to capital (equipment) costs. This omission is due to lack of data on temporal and regional variations in prices of household equipment. (This is especially true for the major energy end uses, space and water heating equipment.) This lack of sensitivity to equipment price means that assumed changes in equipment efficiency are treated in the model either as if there were no corresponding change in equipment price or as if the change in equipment price was immaterial. Neither assumption is plausible.

To some extent we expect to overcome the defects described in 2 and 3. Using 1970 state level data on equipment saturations, fuel prices, and equipment prices, we are estimating a detailed set of market-share equations for gas, oil, electricity, and other/none for space heating, water heating, cooking, and air conditioning. These are sensitive to fuel prices, incomes, and equipment prices. These models (to be described in a forthcoming report) have a structure theoretically more appealing than those from which the elasticities used here are derived; and they include equipment prices. We also plan to develop dynamic models of market penetration, using annual time-series data.

A large data base (for each state each year from 1946 to 1974) is being used to develop econometric models of household fuel use for electricity, gas, and oil. These models will then replace the combined household/commercial sector model used to drive our elasticity estimator.

4. Engineering changes in equipment and structures are exogenous to the model. We are now developing simple engineering models (essentially repeated applications of the first law of thermodynamics plus empirical data) to use in evaluating alternative equipment designs and their impacts on energy requirements. We plan to develop similar models to evaluate changes in capital costs. These models will then be used to provide equipment efficiency and cost information to the overall energy use simulation.

5. Because the model deals with energy use at the national level, regional variations in residential energy uses because of differences in climate, fuel prices, incomes, and population growth are not explicitly recognized. We plan to develop a set of regional residential models for the nine U.S. Census divisions.

6. Ours is an energy demand model; energy supplies appear only through the exogenously specified fuel prices. To account for future energy supply options and to ensure that our fuel price inputs are realistic, we plan to operate our model in conjunction with the energy system optimization models developed at the Brookhaven National Laboratory.

7. Most of the data used to develop this model (and its predecessors) are from the 1960s, a time when fuel prices were low and declining, incomes were steadily rising, and attitudes toward energy and energy conservation were very different from what they are now. To the extent that attitudes toward energy use have changed, the model's results are in error. Although the model captures some of the economic and demographic determinants of household fuel use, intangibles such as comfort, convenience, reliability, safety, attitudes of neighbors, and whatever else goes into decisions on household equipment choice and usage are not captured by our model.

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