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Conservation
—
Division of Buildings
and
Community Systems

An Improved Engineering-Economic Model of Residential Energy Use

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OAK RIDGE NATIONAL LABORATORY

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ENERGY DIVISION

AN IMPROVED ENGINEERING-ECONOMIC MODEL
OF RESIDENTIAL ENERGY USE

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ABSTRACT

An improved version of the ORNL residential energy use model was developed to simulate energy use in the residential sector from 1970 through 2000. The model provides considerable detail on annual energy uses by fuel, end use, and housing type; and also estimates annual equipment installations and ownership, equipment energy requirements, structural thermal integrities, fuel expenditures, equipment costs, and costs for improving thermal integrities on new and existing housing units. Thus, the model provides considerable detail on residential energy uses and associated costs. These details are useful for evaluating alternative energy conservation policies, programs, and technologies for their energy and economic effects during the next quarter century.

The present version of the model deals with four fuels, eight end uses, and three housing types. Each of these 96 fuel use components is calculated each year as a function of stocks of occupied housing units and new construction, equipment ownership by fuel and end use, thermal integrity of housing units, average unit energy requirements for each equipment type, and usage factors that reflect household behavior.

Simulations of energy use from 1960 to 1975 show that the model accurately predicts historical data on aggregate energy use, energy use by fuel, energy use by end use, and equipment ownership market-shares.

A reference projection developed with the model shows residential energy use growing from 17.5 GGJ (10^{18} joules) in 1975 to 18.5 GGJ in 1980 and 26.6 GGJ in 2000, with an average annual growth rate of 1.7%. Electricity increases its share of the energy budget from 44% in 1975 to 67% in 2000. Shares provided by gas, oil, and other fuels all decline during this period.

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AN IMPROVED ENGINEERING-ECONOMIC MODEL
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1. INTRODUCTION

This report describes the structure, inputs, validation, and operation of an improved version (Version III) of the ORNL residential energy use model. The purpose of this work is to provide an analytical tool to evaluate a variety of energy conservation policies, programs, and technologies for their effects on energy use, energy costs, and capital costs over time.

The improved model deals with energy use at the national level for four fuels* (electricity, gas, oil, other); eight end uses (space heating, water heating, refrigeration, food freezing, cooking, air conditioning, lighting, other); and three housing types (single-family units, apartments, mobile homes). Household energy use (for each fuel/end use/housing type combination) is computed in response to changes in: stocks of occupied housing units and new residential construction, equipment ownership by fuel and end use, thermal integrity of housing units, average unit energy requirements for each type of equipment, and usage factors that reflect household behavior.

* Electricity use figures are in terms of primary energy (3.37 J/J or 11,500 Btu/kwhr from 1970-2000); 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.

Version III of the ORNL model^{*} differs from the original version of the program¹ in several ways:

1. New equipment choices (market shares among fuels) are functions of both operating costs (fuel prices, equipment efficiencies) and equipment prices. The original version included only operating costs as explanatory variables for equipment choices.
2. Model outputs now include detailed information on the economics of residential energy use (fuel costs and capital costs) as well as information on energy uses.
3. The number of end uses is increased from six to eight. The new end uses are food freezing (split from refrigeration) and lighting (split from other).
4. Version III deals explicitly with new equipment sales and then calculates equipment ownership from new installations. The original model calculated equipment ownership each year directly and then inferred new equipment sales.

Figure 1 is a schematic diagram of the energy model. The demographics submodel (described in Section 2) calculates stocks of occupied housing units by type for each year of the simulation. Based on calculations of household formation and retirements from the existing stock of occupied housing units, new construction requirements are calculated for each year to ensure that the stock of occupied housing units matches demand (the number of households that year).

The economic submodels (Section 3) calculate elasticities that determine the responsiveness of households to changes in economic variables: incomes, fuel prices, equipment prices. Elasticities are calculated for each of the three major household fuels for each of the eight end uses. Each fuel price and income elasticity is decomposed into two elements — an elasticity of equipment ownership (E_o) and an

^{*} All the Version II improvements are incorporated in Version III. No separate documentation for Version II exists.

Fig. 1. Schematic of ORNL residential energy use model.

elasticity of equipment usage (E_u). The first gives changes in equipment ownership in response to changes in fuel prices, equipment prices, and incomes. The second gives the responsiveness of equipment usage (with ownership held constant) to changes in own-fuel prices and incomes. These submodels calculate a total of 272 elasticities.

The technologies submodels (Section 4) evaluate changes in equipment energy requirements and purchase price as functions of alternative designs. Detailed engineering submodels were constructed for gas and electric water heaters and for refrigerators. We synthesized data from a number of sources to infer relationships between equipment energy use and initial cost for the other end uses considered in Version III.

Section 5 describes the operation of the overall simulation model. Basically, the simulation model combines outputs from the various submodels (Fig. 1) with appropriate initial conditions for 1970 and boundary conditions (policy variables) for the 1970-2000 period. Outputs from the simulation model include 96 fuel use components (Q_t^{ikm}) for each year (t): 4 fuels (i) $\times$ 8 end uses (k) $\times$ 3 housing types (m).^{*} The model also calculates annual fuel expenditures, equipment costs, and capital costs for improving thermal integrity of new and existing structures at the same level of detail. Each fuel use component is determined in the simulation program as the product of five factors:

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

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.

* Forty-two of these 96 cells are empty; for example, oil-fired refrigerators.

Section 6 compares model predictions with historical data from 1960 through 1975. Model predictions are compared with data for each fuel and for equipment ownership market-shares in 1970, 1973, and 1974. Finally, distributions of fuel by end use for 1970 and 1974 from the model are compared with independent estimates.

Section 7 presents two projections of residential energy use to the year 2000. Independent estimates of fuel prices and incomes are used as inputs to the model. Two sets of assumptions concerning technical improvements in equipment and structures are postulated. The energy and economic costs of these projections are compared.

The final section summarizes the key features of the present version, discusses additional efforts underway to further improve the model, and describes some of the applications of the model for our project sponsors, the Federal Energy Administration (FEA) and the Energy Research and Development Administration (ERDA).

Table 1 summarizes the key features of Version III. Because of these features the model is useful for evaluating various conservation policies, programs, and technologies. As examples, model outputs can be used to evaluate: (1) appliance efficiency standards, (2) thermal standards for new residential construction, (3) alternative fuel price strategies, and (4) financial incentives for retrofits of existing structures. For each of these policies and programs, model outputs estimate energy use changes by fuel and end use over time; in addition, outputs include changes in energy costs, capital costs for equipment, and costs for upgrading structural thermal integrity. These cost figures allow one to develop simple benefit/cost measures for each program.

Table 1. Key features of the ORNL residential energy use model

Explicit	Sensitive to demographic, economic, and technological determinants of energy uses
Simulation	Based on household behavior about equipment and structures purchases and uses
Dynamic	Incorporates time features of equipment and structures lifetimes and behavioral lags
Detailed	Calculates 96 fuel/end use/building type components for each year for energy, energy costs, and capital costs

The model can also evaluate the effects of various energy conservation technologies, including R&D projects. For example, model outputs can estimate the energy and economic effects of offering an improved space heating system to consumers (e.g., a gas-fired heat pump) by specifying the efficiency and capital cost characteristics of the new system.

Finally, the model produces projections of residential energy use that are both detailed and internally-consistent. Projections include estimates of annual fuel use for each fuel/end use/housing type, estimates of equipment ownership and new equipment market shares by fuel and housing type, thermal integrities of structures by type of housing unit, and usage factors by fuel and end use.

2. HOUSING MODEL

Figure 2 shows the structure of the housing model used in Version III. It differs from the housing model used in the original energy model^{1,2} in two ways:

- 1.. The new housing model evaluates changes in household formation (for each of 7 age groups) as functions of income and last year's household formation.. The original version used projections of household formation from the Bureau of the Census³ that were based on different demographic assumptions and no explicit economic assumptions..
- 2.. The new model calculates stocks of occupied housing units and new construction for each of the nine Census Divisions* as well as for the nation as a whole.. The original model dealt with the nation only..

*: These regional housing projections will be used with residential energy use models now being developed for each of the nine Census divisions..

Fig. 2.. Schematic of ORNL housing model..

Inputs required to run the model include:

1. population by age group and year,
2. per capita income by year,
3. housing occupancy by type of unit and age of household head for 1970 and 2000,
4. retirement rates for each housing type.

The model first calculates the number of households by age of household head each year as the product of population and headship rate.* Headship rates are obtained from regression equations developed using historical data from 1951-1975. The form of the assumed relationship is:

$$\ln \left(\frac{H_i}{0.75 - H_i} \right)_t = A_i + B_i Y_t + C_i \ln \left(\frac{H_i}{0.75 - H_i} \right)_{t-1},$$

where

A, B, C are coefficients determined from the regression analysis,

H_i is the headship rate for households in age group i (7 age groups: 15-24, 25-29, 30-34, 35-44, 45-54, 55-64, 65+),

Y is real per capita income (deflated by the Consumer Price Index, CPI),

t is the year of interest, and t-1 is the previous year.

Historical data on households and population by age group are from the Bureau of the Census.^{4,5} Income data are from the Council of Economic Advisors.⁶

* Headship rate is defined as household heads in age group i/population in age group i.

We used the logit formulation to ensure that H remains between its lower and upper bounds (0.0 and 0.75, respectively) for all values of the right-hand side. The theoretical upper limit is 1.0. However, it is impossible that all adults would ever live in one-person households; we selected the value 0.75 for the upper limit based on conversations with T. C. Marcin (U.S. Forest Service) and our own judgment. Upper limits in the range 0.7-1.0 have little effect on headship rate projections to the year 2000, except under high income growth assumptions. Additional work is needed to develop a better set of upper limits for each age group.

Table 2 shows the coefficient estimates for the seven age groups. We also tried other model formulations before adopting the one shown. In particular, we tested models using the housing component of the CPI⁶ as an indicator of housing prices; however, the variation in $\text{CPI}_{\text{housing}}/\text{CPI}$ was so small that the coefficients for this term were statistically insignificant.

The national projection of households (identically equal to stock of occupied housing units) is next disaggregated for each of the nine Census divisions. In performing this disaggregation, we assume that each region's share of the nation's households exactly corresponds to that region's share of the nation's population. In 1970, the number of people per household was almost identical across Census divisions. Population projections for each region are obtained from the Census Bureau.⁷

Households in each region for each year are then shared among the three housing types on the basis of an assumed housing choice matrix.

Distributions of housing types for each region are different, according to the distribution of housing types in 1970.⁸

Table 2.. Estimated household formation equations^a

$$\text{Dependent variable: } \ln \left(\frac{H_{it}}{0.75 - H_{it}} \right)$$

Estimated coefficients					
Age group i	Constant	Per capita income	Lagged dependent variable	R ²	D-W ^b
<24	-0.538 (-1.7)	0.0000891 (2.2)	0.806 (5.8)	0.88	2.3
25-29	-0.524 (-3.1)	0.000267 (3.3)	0.369 (1.8)	0.94	2.2
30-34	-0.072 (-1.1)	0.0000937 (1.8)	0.694 (3.9)	0.91	1.7
35-44	0.035 (0.9)	0.000212 (3.6)	0.107 (0.5)	0.92	1.6
45-54	0.302 (2.7)	0.0000659 (2.3)	0.457 (2.5)	0.70	1.7
55-64	0.350 (2.9)	0.000145 (3.5)	0.340 (1.8)	0.81	1.6
>65	-0.197 (-1.8)	0.000398 (2.9)	0.385 (1.8)	0.94	2.0

^a All equations are estimated using ordinary least squares with data from 1951 through 1975 (23 observations). Figures in parentheses are computed t-ratios.

^b Examination of the Durbin-Watson statistics suggests the possibility of serial correlation of disturbances for the fourth and sixth equations. Although the modified D-W statistic is more appropriate for equations containing lagged dependent variables, we do not report these statistics because they apply only for large samples. In future revisions of the housing model, we will specify an autoregressive form of the household formation equation.

Finally, the number of new housing units constructed each year in each region is calculated based on new households in each region and retirement of existing housing units (determined by retirement rates input to the model).^{*}

We developed several projections of household growth, housing stocks, and new construction using our model plus different assumptions concerning income growth and housing choices in the year 2000. All our projections assume that population will grow according to the Census Series II projection.⁹ Our reference projection of per capita income is derived from a Data Resources, Inc. (DRI) projection of GNP prepared for ERDA¹⁰ and the Series II population projection. The average annual growth rate of per capita income in this case is 2.5% between 1975 and 2000. For purposes of comparison, we also developed housing projections assuming that per capita income grows at 1.0%/year and 2.0%/year between 1975 and 2000. The DRI projection yields a value of per capita income in 2000 of \$12,000 (1975-\$). The 1% and 2% projections yield values of \$8,200 and \$10,400, respectively. Per capita income in 1975 was \$5,900.

We made two different assumptions about the housing choice matrix (housing type by age of household head) for 2000. The first assumes that housing choices by age of household head remain at their 1970 values.⁸ The second assumes that changes in housing choices that occurred between 1960 and 1970⁸ continue linearly to the year 2000.

^{*} For the 1975-2000 period, the assumed retirement rate for single-family and multi-family units is 0.72%/year; for mobile homes it is 4.0%/year (ref. 2).

Figure 3 shows our projections of occupied housing units (households) obtained with the DRI and 1%/year income assumptions. We also show Census estimates of households for 1970 through 1975⁴ and their high and low household projections to 1990.³ Our projection using the DRI income growth is 3% higher than the high Census projection in 1990. Our projection for a 1%/year income growth is almost identical with the low Census household projection. Our projection for a 2%/year income growth (not shown) is almost identical with the high Census projection.

Figure 4 shows the predicted distribution of housing choices over time using the two housing choice matrices for 2000 discussed above. We also show Census estimates of housing distributions for 1970, 1973, and 1974.^{8,11} The shift away from single-family units that occurred between 1960 and 1970 is continuing. However, recent data show a very slight decline in multi-family occupancy rather than the increase that would be expected from the 1960-70 trends. Finally, recent data show a more rapid shift to mobile homes than the 1960-70 trend would indicate. The two housing choice matrices assumed for 2000 (Fig. 4) seem to cover the range of likely housing distributions between 1970 and 2000.

In summary, the housing model used with Version III is a significant improvement over the original housing model; household formation is now explicitly sensitive to changes in per capita income.

However, much work remains to be done before we have a satisfactory model. Projections of housing choices are now primarily a function of the user's assumptions concerning housing choices in the year 2000; we hope to replace this assumed housing choice matrix with a set of equations that specify housing choices for each age group as functions of income,

Fig. 3. Projections of households, 1970 to 2000.

housing prices, and other relevant variables. Also, outputs from the housing model do not now allow for changes in unit size as incomes and housing prices change. The results presented here implicitly assume that housing sizes remain constant from 1970 through 2000.

Fig. 4. Projected distributions of households by type of housing unit.

3. ECONOMIC MODELS

Development of the detailed elasticities used in the simulation model proceeds in three distinct steps, as illustrated in Fig. 5. The first component of our economic models is a set of econometric models of household demands for electricity, gas, and oil.¹² These models were constructed using a large data base containing variables for each state and each year from 1951 through 1974. Both cross-sectional and dynamic models of household fuel uses were constructed.

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Fig. 5. Schematic of ORNL energy economic models.

The second component is a cross-sectional analysis of residential fuel choices (equipment ownership market-shares) for five major end uses: space heating, water heating, food freezing, cooking, and air conditioning.¹³ These market-share models were constructed using state-level data for 1970.

The third component is a program (Elasticity Estimator¹) that combines overall fuel price and income elasticities from the first set of models and detailed market-share elasticities from the second set of models with certain logical constraints and assumptions. Outputs from this program are the detailed elasticities required as inputs to the residential simulation model.

Each of the three components is described below.

The household fuel demand equations (cross-sectional)¹² are all specified in a log-log (constant elasticity) formulation, with fuel demand per household as the dependent variable. Independent variables include: prices of electricity, gas and oil; per capita income; and two climatic variables (heating degree days and mean July temperature). Estimated elasticities of household demands for electricity, gas, and oil obtained with cross-sectional models for 1951, 1955, 1960, 1965, 1970, 1971, 1972, 1973, and 1974 are shown in Appendix Tables A-1, A-2, and A-3.

These results show considerable stability over time for the own-price coefficients for electricity and natural gas; long-run elasticities average -1.0 and -2.1, respectively. The own-price elasticity of demand for oil shows more variation, with values ranging from -0.2 in 1955 to -2.5 in 1965; the average of the fuel oil own-price elasticities is -1.3.

Cross-price elasticities for both electricity and gas generally increased in magnitude and statistical significance over time, especially during the last six years of the data series. This suggests that households have become more aware of relative fuel costs and have acted accordingly in their fuel choice decisions.

The absolute magnitude of the own-price elasticity for oil is considerably less (44%) than the cross-price elasticity of oil with respect to the price of gas, averaging 1.8. The implication that the quantity of oil demanded by households is more responsive to changes in the price of gas than changes in the price of oil is counter-intuitive. This result appears to stem from gas availability problems in the North East. Although the price of natural gas tends to be high in large oil-consuming states (Maine, New Hampshire, Vermont), oil consumption is also influenced by the unavailability of gas. Thus the cross-price elasticity of oil with respect to gas price reflects both a price effect and an availability effect.

The per capita income elasticity of demand for natural gas is considerably higher and more stable over time than corresponding values for electricity and oil. The income elasticity of demand for gas averaged 1.8; for electricity and oil these elasticities averaged -0.1 and +0.1 respectively, indicating a clear preference for natural gas in high income states.

The key features of these models¹² are:

1. The models deal explicitly with residential fuel demands, not the combined residential/commercial sector.
2. Improved definitions of residential fuel uses were developed to account for some residential fuel use that is generally allocated to the commercial sector.

3. Three different fuel oil price series were developed and tested.
4. These models are based on a large data base that contains a total of 1128 observations.
5. Both cross-section and dynamic models were developed. Thirteen different equations were estimated for each fuel.
6. Fuel use per household, rather than fuel use per capita, was used as the dependent variable because residential energy use is related more closely to number of households than to number of people.

Additional information on the data used, the dynamic results, and the limitations of this analysis are discussed in ref. 12.

A conditional logit model was used to estimate residential fuel choices¹³ (equipment market-shares): $\ln [(S_i/(1 - S_i))]$ was used as the dependent variable, where S_i is the fraction of households that use fuel i for the particular end use. Independent variables were fuel prices, equipment prices, per capita income, heating degree days (for space heating), cooling degree days (for air conditioning), fraction of households in urban areas (for food freezers), and fraction of households in single-family units (for food freezers).

There are several advantages to the semi-log logit formulation used in ref. 13 relative to models specified previously:

1. The logit formulation ensures that estimated market-shares always lie between 0 and 1 for any set of independent variables.
2. The equations for each end use are estimated with the restriction that the sum of market-shares for the nation must equal 1.0.
3. Equipment prices, as well as fuel prices, are used as explanatory variables.

Table A-4 presents the coefficient estimates obtained with a semi-log logit model for 1970. Additional results for 1970 and 1960 using a

log-log logit formulation are given in ref. 13. Fuel price market-share elasticities evaluated with the coefficients in Table A-4 and the 1970 national market-shares are presented in Table A-5; also shown are elasticities from two other studies. Table A-6 presents equipment price elasticities obtained with the coefficients of Table A-4.

Table A-5 shows that own-fuel price elasticities are all greater than unity, except for gas ranges. Only one of the fuel price elasticities has the wrong sign (demand for oil space heating with respect to electricity price). Most coefficients (Table A-4) are significant at the 10% level or better. These elasticities show that consumers respond to fuel price changes in selecting among alternative equipment choices.

Almost all equipment price elasticities are greater than unity and larger than the corresponding fuel price elasticities (Tables A-5 and A-6). The equipment price coefficients all have the correct signs and are generally statistically significant at the 10% level or better. These results show that equipment and appliance prices are important determinants of residential fuel choices.

The third portion of our economic models is the Elasticity Estimator.¹ The driving force for the detailed elasticities produced with this program is a set of overall fuel price and income elasticities for household fuel demands; these are based on our synthesis of the ORNL results and those from other studies of the household and combined household/commercial sector.¹²

Based on our synthesis of equipment ownership market-share elasticities from ref. 13 and related studies, we developed own-, cross-price, and income elasticities of equipment ownership in terms of their relationships to comparable values for space heating. These elasticity

ratios are combined with data on 1970 fuel uses¹ by fuel and end use to derive long-run elasticities for each end use, as follows:

$$E_{lr}^{ij1} = \frac{E_H^{ij}}{f^{i1} + \sum_{k=2}^8 f^{ik} (E^{ijk}/E^{ij1})},$$

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

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 ($k = 1$). E_H^{ij} is the elasticity of household demand for fuel i with respect to price or income j .

The above equation assumes that the ratio between the overall price (or income) elasticity for a particular end use and the equipment market-share elasticity for that end use is the same for all end uses. Then the above equation follows from the requirement that the weighted sum of elasticities over all end uses must equal the overall elasticity, i.e.:

$$E_H^{ij} = \sum_{k=1}^8 f^{ik} E^{ijk}.$$

These long-run fuel price and income elasticities are disaggregated into two components for ownership and usage; $E = E_o + E_u$. The usage elasticity E_u is, by definition, equal to zero for all cross-price

* $\sum_{k=1}^8 f^{ik} = 1.0.$

terms. We constrained the two long-run elasticities, relative to each other, to $E_o/E_u = 3$. The ratio of 3 was derived by comparing the weighted sum of equipment market-share elasticities with the overall elasticity. This comparison yielded an average ratio of $E_H/E_o = 4/3$ for the various own-price and income elasticities. Thus

$$\frac{E_o}{E_u} = \frac{1}{E_H/E_o - 1} = 3.$$

Thus we assume that 75% of the long-run response to a change in own-price or income is due to changes in equipment ownership and 25% is due to changes in equipment usage.* Then (for $i = j$):

$$E_{olr}^{ijk} = \frac{3}{4} \cdot E_{lr}^{ijk} \quad E_{ulr}^{ijk} = \frac{1}{4} \cdot E_{lr}^{ijk}.$$

These equipment ownership and equipment usage fuel price and income elasticities are inputs to the simulation model. The simulation model converts the equipment ownership market-share elasticities (E_{olr}) to new equipment market-share elasticities, (E_{nlr}) using the following relationship:

$$E_{nlr}^{ijk} = E_{olr}^{ijl} \left[\frac{S_i (1 - S_i)}{SN_i (1 - SN_i)} \right],$$

where SN_i is the fraction of new units sold for a particular end use that uses fuel i .

* In the short run, E_o/E_u is less than 3; that is, usage changes are relatively more important in the short run (see Fig. 6).

This relationship between equipment ownership and new equipment elasticities ensures that changes in fuel prices and incomes will leave the sum of new equipment market-shares equal to 1.0 (for small changes around the 1970 values). That is,

$$\sum_{i=1}^4 S_i = 1.0 ,$$

if:

$$\sum_{i=1}^4 E^{ij} S_i (1 - S_i) = 0 .$$

Then

$$\sum_{i=1}^4 SN_i = 1.0 ,$$

only if the above relationship is satisfied.

Values of new equipment price market-share elasticities are derived from the corresponding fuel price market-share elasticities and a set of "real" interest rates input to the simulation program. These interest rates (Table A-7) are determined largely from results in ref. 13 and changes in real fuel prices during the late 1960s. The equipment price elasticities (E_{pnlr}^{ijk}) are calculated as:

$$E_{pnlr}^{ijk} = E_{nlr}^{ijk} \frac{PQ^{jk}}{p^j \cdot EU^{jk}} \left[\frac{r}{1 - (1 + r)^{-t}} \right],$$

where E_{pnlr}^{ijk} is the market-share elasticity with respect to equipment price, PQ^{jk} is the consumer purchase price for that type of equipment, p^j is the price of fuel j , EU^{jk} is the annual energy requirement for a typical piece of equipment that uses fuel j for end use k , r is the real interest rate, and t is the average lifetime for that type of equipment (Table A-8).¹

The dynamics of changes in energy use are determined by two factors: equipment lifetimes and pace of usage changes. Based on the results developed for the original simulation program,¹ and the dynamic equations of ref. 12, we assume that 50% of the usage response occurs in the first year, i.e.,

$$E_{usr}^{ijk} = 0.50 E_{ukr}^{ijk}$$

We also assume that changes in equipment ownership are constrained only by equipment lifetimes.

Figure 6 illustrates the dynamics of energy use in response to a change in gas price for gas water heating. The curves show changes in usage and ownership, and the combined change due to a step increase in gas price in year 1. The usage response is quite rapid: in less than two years the response reaches more than 3/4 of its equilibrium value. However, the response is much slower for equipment ownership: it takes six years to reach 50% of the equilibrium value. Combining these two curves yields a 50% response in four years. Twenty years after the gas price change 90% of the adjustment is complete.

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Fig. 6. Effects of a step change in the price of gas on ownership and usage of gas water heaters.

In summary, the models discussed in this section produce a detailed set of 272 elasticities for use in the simulation model:^{*}

new equipment market-share elasticities (4 choices $\times$ 7 fuel price, equipment price, and income variables $\times$ 8 end uses);

equipment usage elasticities (3 fuels $\times$ 2 own-price and income variables $\times$ 8 end uses).

Unfortunately, the statistical basis for many of our cross-price and income elasticities is weak.^{12,13} Lack of data forced us to make several assumptions to derive the 272 elasticities used in the simulation model. Also, the applicability of fuel price and income elasticities derived with data from a period in which fuel prices were declining to a future in which prices are likely to rise significantly is unknown. Clearly, more work must be done to develop good data series on household fuel uses and prices and on econometric estimation to produce improved elasticity estimates.

4. TECHNOLOGY MODELS

The technology models evaluate relationships between equipment or structure energy intensiveness (inverse of energy efficiency) and changes in capital cost for the present technological "state-of-the-art." Figure 7 is a schematic representation of these models showing

* One can readily change inputs to the elasticity estimator 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.

how the energy and cost analyses are combined to define these relationships.

Fig. 7. Schematic of ORNL residential technology models.

Detailed engineering and cost analyses were conducted for refrigerators¹⁴ and for gas and electric water heaters.^{15,16} A preliminary analysis of alternative designs for gas and electric ranges and their energy use consequences was conducted;¹⁵ however we have not yet completed the corresponding cost analysis. We reviewed the relevant literature for the other end uses (particularly space heating and air conditioning) and synthesized existing information to develop initial estimates of energy use vs. cost.

In a similar fashion, we evaluated changes in heat loss (winter) and heat gain (summer) for a single-family unit as functions of changes in initial cost for different structure designs. We then used these results to infer corresponding relationships for apartments and mobile homes.

Our refrigerator analysis is discussed as an example of the equipment technology models. A computer model was developed to evaluate flows of energy and electricity use in residential refrigerators; the model was then used to evaluate the energy requirements for alternative refrigerator designs.¹⁴

The first portion of the energy model evaluates thermal gains to the refrigerator. The refrigeration system must overcome these heat loads to maintain constant temperatures in the fresh-food and freezer compartments. The thermal load is the sum of: conduction through walls, air changes due to door openings, infiltration around gaskets, energy extraction from food, heat gains from refrigerator heaters and fans, and miscellaneous loads.

The second portion of the model calculates electricity requirements for the compressor based on total thermal load. This part of the model also sums the electricity requirements for heaters and fans.

Outputs from the computer program include all thermal loads, electricity uses, and the fraction of time the compressor runs. The program is written so that the user can change environmental conditions (e.g., room temperature, number of door openings) and refrigerator characteristics (e.g., size, type, wall insulation thickness, compressor efficiency). This allows one to evaluate electricity use changes due to different refrigerator designs.

The following design changes were evaluated with the refrigerator model: changes in insulation thickness and/or type, removal of evaporator fan motor from refrigerated space, use of anti-sweat heater switch, elimination of frost-free feature, improved compressor efficiency, and increased condenser and/or evaporator surface areas. The initial costs for these design changes were obtained from telephone communications with manufacturers and engineers performing similar studies.

Figure 8, which summarizes the results of our refrigerator analysis, shows changes in retail price due to various design changes that reduce refrigerator electricity use. For use in our simulation model, we must convert the points in Fig. 8 into an analytical expression.* Figure 8, and similar graphs of energy use versus initial cost for other types of equipment, show negative first derivatives and positive second derivatives. Applying these constraints to the derivatives ensures that the systems conform to the law of diminishing marginal returns.

A simple two-parameter equation that satisfies the derivative constraints is:

$$E/E_0 = E_{\infty}/E_0 + (1 - E_{\infty}/E_0) e^{-\alpha(C/C_0 - 1)},$$

where

E = energy use (e.g., J/year^{**})

C = initial cost (e.g., 1975-\$)

* Elimination of the frost-free feature saves energy and reduces purchase price. However this design involves a behavioral change on the part of households and is not considered in the energy use vs. initial cost relationship.

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

Fig. 8. Electricity use versus retail price for a typical refrigerator.

E_{∞} , α = parameters. E_{∞} is the asymptotic limit on efficiency improvements and $\alpha(1 - E_{\infty})$ is the slope of the curve when $E = E_0$ (and $C = C_0$).

The subscript ()₀ refers to the reference (1970) unit. That is, E_0 and C_0 are the annual energy requirement and initial cost, respectively, of a typical unit sold in 1970.

Values of E_{∞} and α (obtained with "eyeball" fits) for each of the end uses in the simulation model¹⁴⁻²⁰ are shown in Table A-9. The resultant equations define the optimal (minimum cost) design alternatives for each system.

A similar set of analyses was conducted for single-family structures. Design changes considered for new structures were: additions of wall insulation, ceiling insulation, floor insulation, storm doors, and storm windows. Estimates of changes in winter heat loss and summer heat gain for each design (relative to houses meeting Federal standards in effect in 1970) were compared with the new change in structure cost using estimates from refs. 18 and 21. The net cost change is the increase in construction cost because of additional labor and materials minus the savings for smaller heating and air conditioning equipment.

For existing single-family structures we considered all the design changes listed above except increased wall insulation. The cost change for existing structures does not include a credit for smaller equipment. Our results for gas-heated homes are shown in Fig. 9 for new and existing structures.*

* Thermal integrity (TI or TIN) is defined as the annual heat loss (winter) or heat gain (summer) through the shell of a housing unit. TI and TIN are used in the simulation model relative to their 1970 values, i.e., $TI_{1970} = TIN_{1970} = 1.0$.

Fig. 9. Space heating thermal integrity for single-family units versus increased capital costs.

The analytical equation used in the simulation model to represent the cost/thermal integrity tradeoff for new and existing structures is:

$$TIN/TIN_0 = TIN_{\infty}/TIN_0 + (1 - TIN_{\infty}/TIN_0) e^{-\alpha C/C_0},$$

where

TIN = thermal integrity,

C = change in initial cost due to TI change (1975-\$),

TIN_{∞} , α = are parameters.

We assumed that the improvements for single-family units are also possible for multi-family and mobile home units. We assumed that capital cost changes would be directly proportional to the size (m^2 of floor space) of each unit. This yields the estimates of TIN_{∞} and α shown in Table A-9.

Table A-9 summarizes the energy use/capital cost relationships presently used in the simulation model. We are continuing our engineering analyses to develop better estimates of changes in energy requirement as functions of changes in initial cost. Our present efforts focus on space heating systems and gas and electric ranges. Later, we will examine structure changes for apartments and mobile homes. We will also examine new residential technologies (e.g., solar heating and water heating systems, advanced heat pumps) so that they can be incorporated into our efficiency versus cost relationships (Figs. 7-9).

5. SIMULATION MODEL

The residential energy use simulation model combines outputs from the housing model, economic models, and technology models (Fig. 1); plus appropriate initial conditions for 1970 and policy variables for the 1970-2000 period. Outputs from the model include detailed estimates of

annual national energy use by fuel, end use, and housing type; and corresponding information on equipment installations and ownership, equipment energy requirements, structural thermal integrities, fuel expenditures, equipment costs, and costs for improving thermal integrities of new and existing structures. Figure 10 is a schematic diagram of the simulation model that shows how the various inputs are combined to produce these detailed outputs.

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Fig. 10. Schematic of ORNL residential energy use simulation model.

The basic equation in the simulation model that defines residential use of fuel i for end use k in housing type m during year t is:

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

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.

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.

Stocks of occupied housing units (HT) by type of unit are calculated in the housing model, discussed in Section 2.

The fraction of households of type m that use fuel i for end use k (C^{ikm}) is determined from:

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

where:

R = fraction of last year's equipment stock that is scrapped.

R is related to average equipment lifetime (Table A-8) by

$$R = 1 - \frac{1}{2^{1/t_{\text{average}}}}$$

CN = fraction of new equipment (NU) installed during year t that uses fuel i for end use k in housing type m.

NU = number of new units installed during year t that provide end use k in housing type m. The number of new units installed equals growth in households plus replacement of units that are scrapped in year t.

The fraction of new units (CN) is calculated from the following equation:

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

where:

A, B, C, D = coefficients discussed in Section 3,

X = fuel price,*

EUN = new equipment energy use,

TI = average thermal integrity,

PEQ = new equipment purchase price,*

Y = per capita income.*

* Prices and incomes are expressed in constant 1975-\$ terms.

In these new equipment market-share equations,* consumer choices are functions of both operating cost (fuel price $\times$ equipment energy use) and equipment cost. This formulation provides a strong link within the simulation model between technological changes (in EUN, TI, and/or PEQ) and economic changes (in fuel prices).

The EU terms (average annual equipment energy use) are calculated within the model based on the EUN values input to the model, equipment lifetimes, and existing stocks of equipment:

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

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

The usage terms (U) are determined by equations of the form:

$$\ln U_t^{ik} = E^{ik} + F^{ik} \cdot \ln (X_t^j \cdot EU_t^{jkm} \cdot TI_t^{jkm}) + G^{ik} \cdot \ln Y_t + H^{ik} \cdot \ln U_{t-1}^{ik}.$$

where

E, F, G, H = coefficients determined from models discussed in Section 3.

* We use an upper limit of 1.2 (rather than 1.0) in the logit equation for refrigerators and an upper limit of 2.0 for lighting. Thus we assume that the number of refrigerators per household can increase by no more than 20% and the number of lighting fixtures per household can increase by no more than 100%, relative to 1970 ownership.

Thus the intensity with which households use equipment depends on incomes and the operating cost for that type of equipment. Here again, energy use depends on both technological and economic factors.

The model also requires a set of initial conditions for 1970. These 1970 data include equipment ownership (market-shares),⁸ annual equipment fuel use,^{1,19} equipment prices,^{13,18,22} and new equipment installations — for each fuel/end use/housing type combination. Fuel prices²³ and housing stocks⁸ are also required. These input data and their sources are described in ref. 1.

Finally, a set of boundary conditions for the 1970-2000 period must be input to the model. These inputs include stocks of occupied housing units and new construction (from the housing model of Section 2), fuel prices, incomes, new equipment energy uses and initial costs, thermal integrities for new structures and corresponding capital costs, and thermal integrities for retrofit programs and corresponding capital costs. Changing some or all of these boundary conditions allows the user to evaluate the energy, energy expenditure, and capital cost impacts of various residential energy conservation policies, programs, and technologies.

Outputs produced by the simulation model include 96 fuel use components (Fig. 11) calculated for each year from 1970 through 2000. The model calculates, at the same level of detail, new equipment installations, equipment ownership, average equipment energy use, equipment expenditures, average thermal integrity, thermal integrity expenditures, and usage factors. Thus the outputs produced by the simulation model

are quite detailed; approximately 540 different quantities are calculated for each year of a simulation run.

Fig. 11. Level of detail provided by simulation model for fuel uses, equipment ownership, new equipment installations, fuel costs, equipment costs, and structural thermal integrity costs.

Table 3 shows the long-run fuel price and income elasticities obtained with the simulation model. The model was run six times to obtain these elasticities: once with fuel prices held constant at their 1970 values from 1970 through 2000, and then with prices of individual fuels, income, or all fuels increased by 10% in 1971 and held constant thereafter. The values in Table 3 are the elasticities calculated for

the year 2000. These numbers suggest that, in the long-run, a 10% increase in the price of all fuels will cut energy demand by at least 4.6% (see footnote *a* of Table 3). Similarly, a 10% increase in incomes will, in the long-run, increase energy demand by 5.2%.

Table 3. Long-run elasticities obtained with the ORNL residential energy use model

	Price of: ^a				Income ^b
	Electricity	Gas	Oil	All fuels	
Electricity	-0.84	0.33	0.09	-0.47	0.59
Gas	0.26	-0.93	0.22	-0.45	0.92
Oil	0.19	0.88	-1.64	-0.75	-0.06
Total	-0.34	+0.04	-0.12	-0.46	0.52

^aThese fuel price elasticities account for changes in equipment usage and fuel switching. However, they do not include improvements in equipment and structures efficiencies induced by fuel price changes. Thus, actual own-fuel price elasticities will be higher than those in the table; and actual cross-price elasticities will be lower than those in the table.

^bThese income elasticities include the effects of income on both household formation and fuel use per household.

6. MODEL VALIDATION

Results obtained with the simulation model are compared with historical data for the 1960-1975 and 1970-1975 periods. Comparisons are performed between data and predictions for: annual consumption of electricity, gas, oil, and total residential energy; equipment ownership market-shares; and energy use distributions by end use.

In addition to the input data required for the initial year (1960 or 1970) discussed in Section 5, the user must specify new equipment

market-shares (CN values). Data are not available with which to determine these CN values. Therefore, we adjust these inputs (4 fuels $\times$ 8 end uses = 32 values) so that the model predicts equipment ownership market shares at the next census year (1970⁸ for the run started in 1960, 1973¹¹ for the run started in 1970) with reasonable accuracy.

Also, the user must specify three usage factor ratios (U_{1959}/U_{1960} or U_{1969}/U_{1970}) for electricity, gas, and oil. We adjust these values until the model's predictions for the first few years after the simulation begins are reasonably accurate.*

Because of these 35 "free" inputs, the model accurately predicts energy use for at least a few years after the simulation begins.

Figure 12 compares model predictions of residential fuel uses (electricity, gas, oil, total) with data from 1960 through 1975.²³ The model slightly underpredicts total energy use in the late 1960's and slightly overpredicts energy use in the early 1970's. The discrepancies, however, are minor: the largest error in the model's prediction is 4% (for 1972).

Predictions of gas and electricity use are quite good until the late 1960s. Then, predicted gas use consistently exceeds actual gas use and predicted electricity use is less than actual electricity use. The discrepancy between data and model results is particularly serious for natural gas. This is primarily due to gas shortages and curtailments

* We assume that technical efficiencies for all equipment and structures remain unchanged from 1960-1975. Although it is likely that efficiencies declined because of falling real fuel prices, lack of information prevents us from incorporating these changes into the computer runs.

that first appeared in the late 1960s and became more serious in the early 1970s. These gas supply restrictions also explain the underprediction of electricity use; electricity use was higher than predicted because of fuel switching caused by gas unavailability (see discussion of Table 5 below). The discrepancy between data and model results reaches 20% in 1974 and 1975 for gas. These discrepancies may also be due to changes in electricity and gas rate structures, gas and electricity advertising, household tastes, and other variables not included in the model.

Fig. 12. Comparisons of residential energy use data and model predictions, 1960 to 1975.

Predictions of oil use are good, although the model consistently underpredicts oil use (10-12%) from the mid-1960s through 1975. The sharp decline in oil use that occurred between 1973 and 1974 is captured by the model.

Table 4 presents values of the mean square percentage error (MSPE)^{*} of the model predictions for the 1960-75 and 1970-75 periods from the 1960-75 run and for the 1970-75 period from the 1970-75 run. These MSPE values show that the 1960-75 run does a much better job for the full 15 years than for the last five years. However, the MSPE for total residential fuel use is quite low for both periods. Fortunately, the errors in predicting individual fuel uses tend to cancel each other.

$$* \text{MSPE} = 100 \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{\text{prediction}_i - \text{data}_i}{\text{data}_i} \right)^2}$$

Table 4. Comparison of residential energy use predictions and data

	Mean square percentage error (%)		
	1960-75 simulation		1970-75 simulation
	1960-75	1970-75	1970-75
Electricity	3.3	5.2	3.1
Gas	8.8	14.2	3.8
Oil	8.7	12.4	2.5
Total	3.0	3.5	2.9

Starting the model in 1970 yields much smaller values for MSPE than those obtained for the same five year period with the 1960-75 run. The 35 "degrees of freedom" implicit in the 1970 CN and 1969/1970 U values start the simulation in the right direction. The major difference between the two simulation runs concerns gas use. Starting the model with 1970 data implicitly captures some of the effects of natural gas shortages. Thus, the overprediction of gas and underprediction of electricity shown in Fig. 12 do not occur with the 1970-75 run.

Table 5 compares model predictions (from the 1960-75 run) with Census estimates of equipment ownership ratios for 1970, 1973, and 1974^{8,11,24} relative to 1960. (Comparisons between these data and results from the 1970-75 run are not shown because the 1970-75 run yields excellent predictions, primarily because of the user-specified 1970 CN values.) The 1970 predictions are very close to Census data, primarily because we adjusted the 1960 CN values to ensure a close fit. Predictions of electric equipment market-shares for 1973 and 1974 are slightly lower than actual values. Similarly, predicted values of gas equipment ownership for 1973 and 1974 are higher than actual values. These differences are probably due to gas shortages; these errors also account for discrepancies in fuel use predictions shown in Fig. 12.

Predictions of oil equipment market-shares (space heating, water heating) are quite close to the Census estimates. Finally, predictions of freezer and air conditioner ownership are good.

Table 6 shows a comparison between the 1960-75 simulation predictions of residential energy use by end use for 1970 and 1974 with estimates obtained from refs. 1, 11, 19, and 23. Predicted distributions

Table 5. Comparison of actual and predicted values of equipment ownership market-share ratios^a

	1970/1960		1973/1960		1974/1960	
	Actual	Model	Actual	Model	Actual	Model
Space heating						
Electricity	4.28	4.22	5.78	4.94	6.61	5.17
Gas	1.28	1.26	1.28	1.32	1.29	1.34
Oil	0.80	0.80	0.77	0.74	0.73	0.72
Other/none	0.49	0.53	0.41	0.43	0.38	0.40
Water heating						
Electricity	1.25	1.26	1.39	1.34	1.44	1.37
Gas	1.16	1.17	1.15	1.20	1.14	1.20
Oil	0.84	0.85	0.79	0.82	0.78	0.80
Other/none	0.49	0.43	0.39	0.30	0.37	0.27
Freezers	1.53	1.54	1.71	1.69	1.77	1.74
Cooking						
Electricity	1.32	1.32	1.45	1.39	1.50	1.40
Gas	0.96	0.94	0.89	0.94	0.87	0.95
Oil	0.45	0.45	0.09	0.36	0.09	0.36
Other/none	0.58	0.60	0.55	0.49	0.52	0.46
Air conditioning						
Room	2.38	2.39	2.87	2.82	2.90	2.97
Central	5.63	5.58	8.84	6.79	9.95	7.21
None	0.73	0.73	0.61	0.66	0.58	0.63

^aActual equipment ownership market-shares are from refs. 8, 11, and 24.

Table 6. Comparison of actual and predicted household energy end use distributions^a

	1970 (percent)		1974 (percent)	
	Actual	Model	Actual	Model
Space heating	56	57	55	55
Water heating	14	17	14	17
Refrigeration	6	5	6	5
Food freezing	2	2	2	2
Cooking	5	5	5	5
Air conditioning	4	5	6	6
Lighting	5	4	5	5
Other	8	6	7	6
Total	100	101	100	101

^aActual energy end use distributions are estimated from data in refs. 1, 19, and 23.

for both years are quite close to the actual distributions. The model overpredicts energy use for water heating and underpredicts electricity use for refrigerators and for other purposes. The refrigerator underprediction is caused by changes in the characteristics of refrigerators purchased during the 1960s. These new units were larger than their replacements and much more likely to have automatic defrost features. Thus, the new units consumed more electricity than did their replacements. Underprediction of other electricity uses is probably due to lack of disaggregation within the model of these uses: dishwashers, washing machines, clothes dryers, televisions, and other small appliances.

The results presented in this section suggest that the simulation model accurately predicts historical residential energy use trends and patterns for the 1960-1975 period. Close agreements between data and predictions for aggregate energy use, energy use by fuel, energy use by end use, and equipment ownership market-shares lend confidence to our use of the model to simulate future residential energy use trends and patterns.

7. REFERENCE PROJECTION

In this section we develop a reference (baseline) projection of residential energy use from 1975 to 2000. Inputs required include: population, fuel prices, per capita income, new equipment energy efficiencies and initial costs, and thermal integrities and capital costs for both new and existing residential structures. Each of these inputs must be provided for the 1970-2000 period.

We assume that population grows according to the Bureau of the Census series II projection.⁹ Residential fuel prices are from the Brookhaven National Laboratory energy system optimization model (BESOM).¹⁰ BESOM yields prices for electricity, gas, and oil for 1985 and 2000; we linearly interpolate between actual 1975 prices and BNL 1985 prices and between the 1985 and 2000 BNL prices.

Per capita income is derived from a recent Data Resources Inc. projection of GNP prepared for ERDA¹⁰ and the population projection discussed above. Household formation and stocks of occupied housing units are obtained from our housing model using the DRI per capita income and Census population projections. Table 7 shows the values of population, households, fuel prices, and incomes from 1970 to 2000 used to produce the reference projection.

Table 7. Inputs used in the reference projection of residential energy use to 2000

	Population (10 ⁶)	Households (10 ⁶)	Fuel prices (1975-\$/10 ⁹ J)			Per capita income (1975-\$)
			Electricity	Gas	Oil	
1970	204	63.4	2.40	1.39	1.74	5,500
1975	213	70.4	2.64	1.62	2.65	5,940
1980	223	80.4	3.09	2.27	2.86	7,040
1985	234	90.0	3.55	2.93	3.07	7,870
1990	245	99.2	3.50	3.14	3.30	8,860
2000	262	116.7	3.45	3.54	3.75	11,170

We assume that the FEA appliance efficiency program is implemented fully by 1980 and that all new residential equipment and appliances sold between 1980 and 2000 meet the low appliance efficiency targets. We assume that the ASHRAE 90-75 thermal standards for construction of new

single-family and multi-family units are adopted nationwide by 1985. Finally, we assume that about 320 thousand single-family units are retrofit with additional attic insulation each year from 1977 through 1990. Details of our assumptions concerning efficiency changes by fuel and end use are in refs. 25 and 26.

Figure 13 shows the projection of energy use to the year 2000 produced by our model using the inputs discussed above. The model estimates that fuel use will grow from 15.8 GGJ (10^{18} joules) in 1970 to 17.5 GGJ in 1975, 18.5 GGJ in 1980, and 26.6 GGJ in 2000. Average annual growth rate in energy use from 1975 to 2000 is 1.7%, compared with 3.4%/year from 1950 to 1975.²³ Energy use per household declines at an average annual rate of 0.3% between 1975 and 2000, compared with an average growth of 1.4%/year between 1950 and 1975.²³ Growth in energy use to the year 2000 is slower than during the past 25 years because of higher and rising fuel prices, slower growth in per capita income, and assumed improvements in equipment and structures efficiencies.

Figure 14 shows the distribution of energy use by fuel. Electricity use grows rapidly at 3.4%/year from 1975 to 2000, while gas and oil uses grow at 0.3% and -1.5%/year, respectively. These differences in fuel use growth are due to historical equipment choice preferences (ref. 23), different fuel price trajectories (Table 7), and differences in price elasticities for each fuel (Table 3). Because of these changes, the share of household energy accounted for by electricity increases from 44% in 1975 to 67% in 2000.

The distribution of energy by end use is shown in Fig. 15. Space heating (the most important end use for the entire period) declines in

Fig. 13. Reference projection of residential energy use to 2000.

Fig. 14. Reference projection distribution of residential energy use by fuel.

importance from 53% in 1975 to 45% in 2000. Air conditioning, on the other hand, increases its share of the total from 7% to 12% between 1975 and 2000. Shares of energy accounted for by other end uses remain nearly constant.

To evaluate the energy and direct economic impacts of the three conservation programs assumed in this projection (appliance efficiency standards, thermal standards for new construction, retrofit of single-family units), we developed a projection that did not include any of these programs. This alternative run uses the same inputs for population, households, fuel prices, and incomes given in Table 7; however, for this case we assume that efficiencies for all new equipment and thermal integrities for all structures do not change during the 1970-2000 period.

Fig. 15. Reference projection distribution of residential energy use by end use.

Table 8 compares the energy and direct economic differences between the two projections. The conservation programs save increasing quantities of energy as time passes: 0.7 GGJ in 1980, 2.0 GGJ in 1990, and 3.3 GGJ in 2000. These programs are also economically attractive; the present worth (in 1977, at a real interest rate of 10%) of the time stream of fuel expenditure reductions is greater than the present worth of the additional outlays for equipment and structures. A simple benefit/cost ratio for these programs over the period considered is 2.1 (= \$40 billion saved in fuel/\$19 billion spent on equipment and structures).

Table 8. Residential energy use with and without conservation programs^a

	Run 1	Run 2	% difference
Fuel use (10^{18} J/yr)			
1980	19.2	18.5	-4
1985	21.0	19.6	-7
1990	23.6	21.6	-8
2000	29.9	26.6	-11
Present worth of 1977-2000 expenditures @10% (10^9 1975-\$)			
Fuel	635	595	-6
Equipment	164	177	+8
Structures	0	6	
Total	799	778	-3

^aRun 1 assumes no improvements in energy efficiency for either equipment or structures. Run 2 assumes implementation of the FEA appliance efficiency targets (low) by 1980, adoption of the ASHRAE 90-75 standards for new construction of single-family and multi-family units by 1985, and a mild retrofit program for single-family units constructed before 1974 in force from 1977 through 1990.

The results of Table 8 suggest that these conservation programs save both energy (43 GJ between 1977 and 2000) and money (\$21 billion present worth of cumulative savings). A forthcoming report evaluates the energy and economic benefits of various conservation programs, singly and in combination.²⁶

8. SUMMARY

The model developed here simulates national energy use on an annual basis for four fuels, eight end uses, and three housing types. Each of these fuel use components is determined within the model as a function of housing stocks and new construction, equipment installations and ownership by fuel and end use, energy efficiencies for new and existing stocks of equipment, thermal integrities for new and existing housing units, and usage factors that reflect household behavior. These factors, in turn, are functions of fuel prices, equipment prices, incomes, and technologies. Thus, the residential simulation model is sensitive to the major demographic, economic, and technological determinants of residential energy use.

Comparisons of model results with data from 1960 to 1975 show that the model accurately predicts residential energy use in aggregate, by fuel, and by end use. Predictions of equipment ownership market shares are also good.

We are using this model extensively for our program sponsors, ERDA and FEA, to evaluate a variety of conservation programs. For FEA, we examined the energy and economic impacts of different appliance efficiency standards, adoption of the ASHRAE 90-75 and alternative standards

for construction of new residences, and tax credits for retrofitting single-family homes. For ERDA, we evaluated the energy and economic benefits of federal RD&D programs to develop improved space heating and cooling systems and high-efficiency appliances. Our residential model was also used in the National Academy of Sciences study on nuclear and alternative energy systems (CONAES) to develop alternative projections of residential energy use given different fuel price and income assumptions.

The present model is much more flexible, powerful, and detailed than was the original model. In particular Version III: (1) is sensitive to capital costs as well as to operating costs, (2) provides detailed outputs on the economics of residential energy use, (3) includes two additional end uses, and (4) deals explicitly with new equipment installations. Nevertheless, there still remain limitations that need to be overcome. These include:

1. Regionalization of Model. The present model deals with energy use at the national level. Therefore, projections do not account for regional differences in climate, equipment ownership choices, fuel availability, fuel prices, incomes, population growth, and housing choices. We compiled the input data needed to run our energy model for each of the nine U.S. Bureau of the Census divisions. This will allow us to evaluate the regional effects of national programs as well as the regional effects of regional programs.

2. Improved Characterization of Residential Technologies. We developed detailed engineering and cost models for residential refrigerators and gas and electric water heaters. However, the relationships between equipment energy use (or structural thermal integrity) and capital cost input to the simulation model for other end uses and building types are based on our synthesis of a rather limited literature. Additional work is needed to develop meaningful energy use/capital cost relationships for all residential equipment and structures. We plan to continue our work in this area and to update our synthesis of other research.

3. Endogenous Determination of Equipment Efficiencies and Structural Thermal Integrities (Market Penetration). A change in fuel price will induce three responses on the part of households: changes in usage

of existing stocks of equipment, changes in fuel choice when purchasing new equipment, and selection of new equipment and structures with different efficiencies. Version III of the energy model correctly incorporates the first two responses. The third response is not endogenous to the model; the user must specify changes in efficiency and provide these changes as inputs to the model. We are developing a new model (Version IV) that endogenously determines changes in new equipment energy efficiencies and new structures thermal integrities as functions of fuel prices, fuel and equipment price elasticities, and the technological characteristics for each equipment and structure type. The user will specify the range of technologies available to households for each fuel/end use combination; the model will then estimate market penetrations for each technology over time.

4. Improved Elasticity Estimates. The weakest part of the present model relates to the fuel price, equipment price, and income elasticities. These elasticities are obtained with inadequate data, poorly specified models, and are based on a time period that may not relate well to future changes. Fortunately, new data are becoming available with which to develop improved econometric models of household fuel demands.

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REFERENCES

1. E. Hirst, W. Lin, and J. Cope, *An Engineering-Economic Model of Residential Energy Use*, Oak Ridge National Laboratory, ORNL/TM-5470, July 1976.
2. T. C. Marcín, *Projections of Demand for Housing by Type of Unit and Region*, Agriculture Handbook No. 428, U.S. Department of Agriculture, May 1972; also, T. C. Marcín, *The Effects of Declining Population Growth on the Demand for Housing*, General Technical Report NC-11, U.S. Department of Agriculture, 1974.
3. Bureau of the Census, "Projections of the Number of Households and Families: 1975 to 1990," *Current Population Reports*, Series P-25, No. 607, U.S. Department of Commerce, August 1975.
4. Bureau of the Census, "Marital Status and Living Arrangements: March 1975," *Population Characteristics*, Series P-20, No. 287, U.S. Department of Commerce, December 1975; also earlier annual issues.
5. Bureau of the Census, "Estimates of Population of the United States by Age, Sex, and Race: 1970-1975," *Current Population Reports*, Series P-25, No. 614, U.S. Department of Commerce, November 1975; also earlier reports.
6. Council of Economic Advisors, *Economic Report of the President*, January 1976.
7. Bureau of the Census, "Preliminary Projections of the Population of States: 1975 to 1990," *Population Estimates and Projections*, Series P-25, No. 477, U.S. Department of Commerce, March 1972.
8. Bureau of the Census, *1970 Census of Housing, Detailed Housing Characteristics, United States Summary*, HC(1)-B1, 1972; also 1960 and 1950 Censuses of Housing, U.S. Department of Commerce.
9. Bureau of the Census, "Projections of the Population of the United States: 1975-2050," *Current Population Reports*, Series P-25, No. 601, October 1975.
10. S. Carhart, personal communication, Brookhaven National Laboratory, December 1, 1976.
11. Bureau of the Census, *Annual Housing Survey: 1974, General Housing Characteristics for the United States and Regions*, H-150-74A, U.S. Department of Commerce, 1976; also 1973 Survey.
12. S. Cohn, E. Hirst, and J. Jackson, *Econometric Analyses of Household Fuel Demands*, Oak Ridge National Laboratory, ORNL/CON-7, February 1977.

13. W. Lin, E. Hirst, and S. Cohn, *Fuel Choices in the Household Sector*, Oak Ridge National Laboratory, ORNL/CON-3, October 1976.
14. R. Hoskins and E. Hirst, *Energy and Cost Analysis of Residential Refrigerators*, Oak Ridge National Laboratory, ORNL/CON-6, January 1977.
15. J. D'Acierno, R. Bertolami, and E. Chao, *Energy Consumption in Residential Gas and Electric Water Heaters and Ranges*, Oak Ridge National Laboratory, ORNL/MIT-226, February 1976.
16. R. Hoskins and E. Hirst, *Energy and Economic Analysis of Residential Gas and Electric Water Heaters*, Oak Ridge National Laboratory, forthcoming.
17. C. R. Montgomery, statement before the U.S. Senate Subcommittee on Antitrust and Monopoly, August 26, 1976.
18. J. G. Delene and J. B. Gaston, *A Regional Comparison of Savings from Various Residential Energy Conservation Strategies*, Oak Ridge National Laboratory, ORNL/TM-5146, February 1976.
19. S. H. Dole, *Energy Use and Conservation in the Residential Sector: A Regional Analysis*, Rand Corp. Report R-1641-NSF, June 1975.
20. J. C. Moyers, *The Room Air Conditioner as an Energy Consumer*, Oak Ridge National Laboratory, ORNL/NSF/EP-59, October 1973.
21. J. C. Moyers, *The Value of Thermal Insulation in Residential Construction: Economics and the Conservation of Energy*, Oak Ridge National Laboratory, ORNL/NSF/EP-9, December 1971.
22. Statistical Reporting Services, *Agricultural Prices, Annual Summary 1975*, U.S. Department of Agriculture, June 1976; also earlier annual issues.
23. E. Hirst and J. Jackson, "Historical Patterns of Residential and Commercial Energy Uses," Oak Ridge National Laboratory, September 1976; to be published in *Energy* 2(2), 1977.
24. Billboard Publications, Inc., *Merchandising Week*, 107(8), February 24, 1975; also earlier annual statistical issues.
25. E. Hirst, "Residential Energy Use Alternatives: 1976-2000," *Science*, 194, December 17, 1976; also E. Hirst, *Residential Energy Conservation Strategies*, Oak Ridge National Laboratory, ORNL/CON-2, September 1976.
26. E. Hirst and J. Carney, "Analysis of Federal Residential Energy Conservation Programs," Oak Ridge National Laboratory, forthcoming.

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Table A-1. Estimated Household Demand for Electricity: Cross-Sectional Model*

Estimation Method: Ordinary Least Squares								
Dependent Variable: $\ln(Q_{elec}/\text{Household})$								
Year	$\ln P_{elec}$	$\ln P_{gas}$	$\ln P_{oil}$	$\ln PCI$	$\ln HDD$	$\ln COOL$	Constant	R^2
1951	-1.039 (-12.48) ^a	0.120 (3.30) ^a	0.347 (1.91) ^c	0.282 (2.24) ^b	0.105 (1.85) ^c	0.021 (0.09)	2.028 (1.48) ^d	0.853
1955	-1.035 (-11.29) ^a	0.089 (2.02) ^b	0.619 (2.47) ^b	0.007 (0.05)	0.100 (2.07) ^b	-0.057 (-0.26)	2.062 (1.58) ^d	0.826
1960	-1.029 (-11.40) ^a	0.094 (1.55) ^d	0.738 (2.77) ^a	0.148 (0.90)	0.115 (1.59) ^d	0.238 (0.93)	0.700 (0.37)	0.803
1965	-1.073 (-11.21) ^a	0.007 (0.12)	0.053 (0.20)	-0.211 (-1.18)	-0.025 (-0.35)	-0.002 (-0.01)	5.54 (2.85) ^a	0.785
1969	-1.082 (-10.66) ^a	0.107 (1.35) ^d	0.029 (0.11)	-0.280 (-1.31) ^d	-0.063 (-0.85)	0.233 (1.02)	4.911 (2.66) ^b	0.781
1970	-1.077 (-10.53) ^a	0.092 (1.27)	0.114 (0.48)	-0.376 (-1.82) ^c	-0.062 (-0.99)	0.467 (1.89) ^c	4.164 (2.48) ^b	0.801
1971	-0.867 (-9.33) ^a	0.121 (1.62) ^d	0.127 (0.52)	-0.397 (-1.80) ^c	-0.115 (-1.77) ^c	0.186 (0.80)	4.735 (2.97) ^a	0.759
1972	-1.069 (-10.32) ^a	0.146 (2.15) ^b	0.037 (0.16)	-0.227 (-1.07)	-0.112 (-1.98) ^c	0.156 (0.72)	5.36 (3.63) ^a	0.793
1973	-1.11 (-12.68) ^a	0.162 (2.68) ^b	0.416 (2.08) ^b	0.199 (1.07)	-0.085 (-1.60) ^d	0.504 (2.49) ^b	2.511 (1.96) ^c	0.834
1974	-1.032 (-14.70) ^a	0.403 (6.30) ^a	0.555 (3.24) ^a	0.007 (0.04)	-0.105 (-2.82) ^a	0.552 (3.05) ^a	0.838 (0.78)	0.866

*The figures in parentheses are t-statistics; R^2 is the multiple coefficient of determination. There are 47 observations in each equation.

^aStatistically significant at the 1% level.

^bStatistically significant at the 5% level.

^cStatistically significant at the 10% level.

^dStatistically significant at the 20% level.

Source: ref. 12.

Table A-2. Estimated Household Demand for Natural Gas: Cross-Sectional Model*

Estimation Method: Ordinary Least Squares							
Dependent Variable: $\ln(Q_{gas}/\text{Household})$							
Year	$\ln P_{elec}$	$\ln P_{gas}$	$\ln P_{oil}$	$\ln PCI$	$\ln HDD$	Constant	R^2
1951	1.309 (3.64) ^a	-1.744 (-11.95) ^a	-0.548 (-0.75)	1.966 (3.84) ^a	-0.129 (-0.74)	3.21 (1.16)	0.821
1955	1.167 (2.99) ^a	-2.039 (-10.20) ^a	-0.449 (-0.39)	2.18 (3.56) ^a	-0.076 (-0.37)	4.57 (1.08)	0.762
1960	0.530 (2.22) ^c	-2.026 (-13.72) ^a	-0.329 (-0.46)	1.332 (3.10) ^a	0.036 (0.25)	6.58 (2.04) ^b	0.835
1965	0.381 (1.21)	-1.539 (-9.47) ^a	0.348 (0.41)	1.590 (2.71) ^a	0.116 (0.71)	1.895 (0.48)	0.725
1969	0.197 (0.86)	-2.368 (-14.62) ^a	-0.656 (-1.14)	1.684 (3.52) ^a	0.144 (1.19)	8.269 (3.00) ^a	0.848
1970	0.193 (0.75)	-2.42 (-13.39) ^a	-0.521 (-0.88)	1.876 (3.58) ^a	0.174 (1.37)	7.626 (2.56) ^b	0.825
1971	0.225 (1.07)	-2.256 (-13.33) ^a	-0.346 (-0.63)	2.175 (4.36) ^a	0.201 (1.80) ^c	5.706 (2.22) ^b	0.826
1972	0.204 (0.75)	-2.091 (-11.67) ^a	-0.569 (-0.93)	1.929 (3.43) ^a	0.254 (2.15) ^b	5.318 (1.89) ^c	0.792
1973	0.520 (1.87) ^c	-2.047 (-10.62) ^a	-1.060 (-1.66) ^d	1.195 (2.01) ^c	0.141 (1.09)	7.323 (2.93) ^a	0.771
1974	0.654 (2.72) ^a	-2.227 (-11.22) ^a	-0.100 (-1.66) ^d	1.771 (2.94) ^a	0.231 (2.12) ^b	6.547 (2.73) ^a	0.781

*The figures in parentheses are t-statistics; R^2 is the multiple coefficient of determination. There are 47 observations in each equation.

^aStatistically significant at the 1% level.

^bStatistically significant at the 5% level.

^cStatistically significant at the 10% level.

^dStatistically significant at the 20% level.

Source: ref. 12.

Table A-3. Estimated Household Demand for Fuel Oil: Cross-Sectional Model*

Estimation Method: Ordinary Least Squares
Dependent Variable: $\ln(Q_{oil}/\text{Household})$

Year	$\ln P_{elec}$	$\ln P_{gas}$	$\ln P_{oil}$	$\ln PCI$	$\ln HDD$	Constant	R ²
1951	0.605 (2.94) ^a	1.106 (13.23) ^a	-0.229 (-0.55)	0.854 (2.92) ^a	0.885 (8.83) ^a	-13.71 (-8.62) ^a	0.880
1955	0.594 (2.46) ^b	1.303 (10.53) ^a	-0.159 (0.22)	0.596 (1.57) ^d	1.148 (9.16) ^a	-16.74 (-6.40) ^a	0.846
1960	0.100 (0.28)	1.799 (8.18) ^a	-1.780 (-1.68) ^c	1.008 (1.58) ^d	1.535 (7.04) ^a	-17.06 (-3.55) ^a	0.797
1965	0.067 (0.159)	1.329 (6.08) ^a	-2.446 (-2.13) ^b	0.355 (0.45)	1.405 (6.40) ^a	-11.12 (-2.08) ^b	0.747
1969	-0.012 (-0.033)	2.250 (8.47) ^a	-1.855 (-1.96) ^c	-0.557 (-0.71)	1.611 (8.08) ^a	-17.27 (-3.82) ^a	0.813
1970	-0.248 (-0.61)	2.298 (8.01) ^a	-1.762 (-1.87) ^c	-0.369 (-0.44)	1.450 (7.20) ^a	-15.86 (-3.35) ^a	0.798
1971	-0.057 (-0.19)	2.376 (8.75) ^a	-1.477 (-1.68) ^c	0.094 (0.12)	1.269 (7.06) ^a	-16.57 (-4.02) ^a	0.798
1972	0.164 (0.48)	2.128 (9.48) ^a	-1.148 (-1.50) ^d	0.240 (0.34)	1.234 (8.34) ^a	-16.83 (-4.77) ^a	0.831
1973	0.497 (1.65) ^d	2.005 (9.57) ^a	-1.244 (-1.79) ^c	-0.483 (-0.75)	1.273 (9.06) ^a	-16.05 (-5.90) ^a	0.817
1974	0.560 (1.90) ^c	1.742 (7.17) ^a	-0.650 (0.88)	-0.801 (-1.09)	1.221 (9.13) ^a	-15.44 (-5.27) ^a	0.784

*The figures in parentheses are t-statistics. R² is the multiple coefficient of determination. There are 47 observations in each equation.

^aStatistically significant at the 1% level.

^bStatistically significant at the 5% level.

^cStatistically significant at the 10% level.

^dStatistically significant at the 20% level.

Source: ref. 12.

Table A-4. Constrained Estimates of the Residential Fuel Choice Models: Semi-log, 1970^a

End Use	Eq. No.	Dependent Variable	Constant	Fuel Price			Equipment Price			Y	HDD	R ²	
				P _e	P _g	P _o	P _{oe}	P _{er}	P _{gr}				P _{ra}
Space Heating	1.1	ln (S _e /1 - S _e)	-1.677 (-0.974)	-16.000 (-8.505) ^b	0.035 (2.198) ^c	6.449 (1.794) ^c	0.059 (0.774)			0.011 (0.764)	-0.0001 (-4.011) ^b	0.83	
	1.2	ln (S _g /1 - S _g)	-2.997 (-1.431) ^d	5.841 (2.553) ^c	-0.250 (-12.950) ^b	0.410 (0.094)	0.179 (1.936) ^c			0.050 (2.721) ^b	-0.0001 (-2.388) ^c	0.90	
	1.3	ln (S _o /1 - S _o)	1.976 (0.740)	-1.097 (-0.376)	0.337 (13.710) ^b	-7.442 (-1.335) ^d	-0.363 (-3.076) ^b			-0.017 (-0.731)	0.0002 (4.240) ^b	0.65	
	1.4	ln (S _{on} /1 - S _{on})	-2.655 (-1.312) ^d	-0.968 (-0.438)	-0.056 (-2.978) ^b	8.787 (2.080) ^c	0.215 (2.400) ^c			-0.099 (-5.622) ^b	-0.0001 (-2.237) ^c	0.79	
Water Heating	2.1	ln (S _e /1 - S _e)	-5.538 (3.779) ^b	-20.000 (-8.578) ^b	0.105 (4.973) ^b	0.484 (0.101)				-0.094 (-4.556) ^b		0.78	
	2.2	ln (S _g /1 - S _g)	-4.253 (-3.105) ^b	12.290 (5.636) ^b	-0.223 (-11.300) ^b	3.662 (0.818)				0.092 (4.763) ^b		0.81	
	2.3	ln (S _o /1 - S _o)	-6.729 (-2.273) ^c	2.337 (0.497)	0.414 (9.713) ^b	-21.610 (-2.236) ^c				0.028 (0.659)		0.61	
	2.4	ln (S _{on} /1 - S _{on})	-2.134 (-1.649) ^d	6.123 (2.972) ^b	-0.013 (-0.703)	10.290 (2.434) ^c				-0.084 (-4.583) ^b		0.65	
Cooking	3.1	ln (S _e /1 - S _e)	2.657 (1.476) ^d	-9.528 (-4.469) ^b	0.068 (2.585) ^c		-2.114 (-2.808) ^b	2.593 (3.692) ^b			-0.047 (-2.515) ^c	0.60	
	3.2	ln (S _g /1 - S _g)	-1.161 (-1.719) ^c	8.132 (3.805) ^b	-0.099 (-3.782) ^b		1.158 (1.534) ^d	-2.070 (-2.939) ^b			0.093 (4.450) ^b	0.48	
	3.3	ln (S _{on} /1 - S _{on})	-4.347 (-3.037) ^b	2.861 (1.687) ^c	0.093 (4.441) ^b		2.391 (3.992) ^b	-1.169 (-2.091) ^c			-0.072 (-4.917) ^b	0.65	
Air Conditioning	4.1	ln (S _{ra} /1 - S _{ra})	-2.092 (-1.716) ^c							-1.064 (-2.180) ^c	0.053 (3.657) ^b	0.0009 (7.590) ^b	0.48
	4.2	ln (S _{ca} /1 - S _{ca})	-7.462 (-3.519) ^b							0.557 (0.655)	0.065 (2.592) ^c	0.0011 (5.306) ^b	0.57
	4.3	ln (S _{on} /1 - S _{on})	3.481 (2.371) ^c							0.638 (1.084)	-0.071 (-4.043) ^b	-0.0012 (-8.346) ^b	0.68
Food Freezing	5.1	ln (S _{ff} /1 - S _{ff})	-0.752 (-0.727)	-2.170 (-1.698) ^c				-0.453 (-1.936) ^c	-0.012 (-2.717) ^c	2.734 (4.434) ^b	0.013 (0.678)		0.61
	5.2	ln (S _{on} /1 - S _{on})	0.752 (0.727)	2.170 (1.698) ^c				0.453 (1.936) ^c	0.012 (2.212) ^c	-2.734 (-4.434) ^b	-0.013 (-0.638)		0.61

^aFigures in parentheses are computed t-ratios; R is the correlation coefficient between the actual and estimated dependent variable.

^bSignificant at 1% level.

^cSignificant at 10% level.

^dSignificant at 20% level.

Source: ref. 13.

Table A-5. Fuel Price Market-Share Elasticities

Fuel Choice	This study (log-log)			This study (semi-log)			Wilson			Anderson			Baughman & Joskow		
	P _e	P _g	P _o	P _e	P _g	P _o	P _e	P _g	P _o	P _e	P _g	P _o	P _e	P _g	P _o
Space Heating															
Electricity	-2.63	+0.44	+1.37	-3.19	+0.38	+1.09	-4.88	+1.20		-2.04	+2.21	+0.55	-2.08	+2.12	+3.30
Gas	+0.39	-1.57	+0.03	+0.57	-1.33	+0.03				+0.17	-1.80	+0.55	+0.23	-1.48	+3.30
Oil	+0.03	+3.51	-1.09	-0.18	+2.95	-1.01				+0.17	+2.21	-1.58	+0.23	+2.12	-7.21
Water Heating															
Electricity	-2.63	+1.05	+0.28	-3.22	+0.93	+0.07	-3.22	+2.10		-1.95	+2.20	+0.26	-1.77	+2.98	+1.00
Gas	+0.88	-1.38	+0.31	+1.19	-1.19	+0.30				+0.66	-1.79	+0.26	+0.97	-2.43	+1.00
Oil	+0.79	+5.20	-4.13	+0.46	+4.42	-3.56				+0.66	+2.20	-2.39	+0.97	+2.98	-9.50
Cooking															
Electricity	-1.05	+0.42		-1.22	+0.48		-1.98	+0.91		-0.63	+1.51		-0.78	+1.18	
Gas	+0.72	-0.56		+0.89	-0.60					+0.43	-1.56		+0.77	-1.15	
Food Freezing															
Electricity	-0.30			-0.34			-0.94			-0.57					

Source: ref. 13.

Table A-6. Equipment Price Market-Share Elasticities

Fuel Choice	Electric equipment price ^a	Gas equipment price	Oil equipment price
Space Heating			
Electricity	-2.30	+1.65	+1.63
Gas	+0.82	-2.24	+2.87
Oil	+1.27	+4.75	-10.66
Cooking			
Electricity	-2.88	+3.04	
Gas	+1.35	-2.08	
Air Conditioning			
Room	-1.76		
Central	+1.10		
Food Freezing			
Electricity	-0.79		

^aPrice of room air-conditioner for air conditioning.

Source: ref. 13.

Table A-7. Real interest rates used in the ORNL residential energy model to determine equipment price elasticities

	Real interest rate (%) for:		
	Electric	Gas	Oil
Space heating			
Electric	6	9	9
Gas	9	6	9
Oil	9	9	6
Water heating			
Electric	12	15	15
Gas	15	12	15
Oil	15	15	12
Refrigeration	15		
Freezing	15		
Cooking			
Electric	15	18	
Gas	18	15	
Air conditioning			
Room	15	17	
Central	17	15	
Lighting	15		
Other			
Electric	15		
Gas		15	

Table A-8. Assumed average equipment lifetimes

	Lifetime (years)
Space heating	15
Water heating	7
Refrigeration	14
Freezing	18
Cooking	13
Air conditioning	9
Lighting	1
Other	10

Table A-9. Equipment and structures technology characteristics

	Electric		Gas		Oil	
	E_{∞}	α	E_{∞}	α	E_{∞}	α
Equipment						
Space heating	0.40	3.0	0.70	10.0	0.70	10.0
Water heating	0.75	8.0	0.70	10.0	0.70	10.0
Refrigeration and freezing	0.45	18.0				
Cooking	0.75	8.0	0.55	16.0		
Air conditioning	0.55	10.0				
New structures						
Single-family	0.45	0.0028	0.40	0.0021	0.40	0.0021
Multi-family	0.45	0.0042	0.40	0.0032	0.40	0.0032
Mobile homes	0.45	0.0056	0.40	0.0042	0.40	0.0042

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21. P. L. Johnson	47. ORNL Patent Office
22. S. I. Kaplan	48-67. EC Section, Pat Love
23. R. S. Livingston	68-270. Debbie Barker

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