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Residential Energy Consumption: An Analysis-of-Variance Study

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Residential Energy Consumption: An Analysis-of-Variance Study

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CONTENTS

FIGURE

TABLES

TABLES (Cont'd)

RESIDENTIAL ENERGY CONSUMPTION: AN ANALYSIS-OF-VARIANCE STUDY

by

D.A. Poyer

ABSTRACT

In this report, tests of statistical significance of five sets of variables with household energy consumption (at the point of end-use) are described. Five models, in sequence, were empirically estimated and tested for statistical significance by using the Residential Energy Consumption Survey of the U.S. Department of Energy, Energy Information Administration. Each model incorporated additional information, embodied in a set of variables not previously specified in the energy demand system. The variable sets were generally labeled as economic variables, weather variables, household-structure variables, end-use variables, and housing-type variables. The tests of statistical significance showed each of the variable sets to be highly significant in explaining the overall variance in energy consumption. The findings imply that the contemporaneous interaction of different types of variables, and not just one exclusive set of variables, determines the level of household energy consumption.

SUMMARY

This report presents the results of three projects that were consolidated into one because of methodological issues and resource constraints. The purpose of these projects was to quantify the relationships between energy consumption and a number of socio-economic and climatic variables -- heating and cooling loads, household income, and household structure. In the process of developing the analytical framework, other explanatory variables, such as housing type, home age, and energy and non-energy prices, were also incorporated into the energy consumption model.

Five models, in sequence, were estimated and tested for statistical significance. Each model incorporated additional explanatory information, embodied in a set of variables not previously specified in the energy demand system. The variable sets were generically labeled as follows:

- Economic variables
- Weather variables
- Household-structure variables

- End-use variables

- Housing-type variables

The variables composing each of these variable sets are listed in Table S.1. Tests showed each of the variable sets to be highly significant in explaining the overall variance in the energy demand model.

The impacts of individual variables on energy consumption were measured at the national level by using the mean values from the 1987 Residential Energy Consumption Survey (RECS) in the calculation of numerical derivatives and consumption elasticities. This study uncovered the following important empirical relationships between the independent variables and energy consumption:

- Each variable set defining the five estimated models – the economic, weather, household-structure, end-use, and housing-type models – was statistically significant in explaining additional variance in the overall (energy demand) model.

- Each individual variable, with the exception of the heat-pump and number-of-children variables, was statistically significant at the 0.05 level of significance. (This means that in replicated samples, the 95% confidence interval would not contain the value of zero.)

- Numerically, housing type has the biggest impact on energy consumption (with all other variables held constant). On the average, living in a single-family (detached or attached) or small multifamily (fewer than five units) home increases energy consumption by 58 to 63 $\times$ 10^6 Btu/yr per household, compared with other home types (primarily mobile homes and large multifamily homes).

- Heating and cooling loads, as expected, affect energy consumption significantly. The typical household, given the average number of heating degree days (65°F base), increases its annual level of energy consumption by about 37 $\times$ 10^6 Btu; cooling load, given the average number of cooling degree days (65°F base), increases the annual level of energy consumption for the average household by 12 $\times$ 10^6 Btu.

- The age of the home has a large effect on energy consumption. On the average, household energy consumption in homes built before 1950 is 27 $\times$ 10^6 Btu/yr higher than that in homes built after 1974; for homes built between 1950 and 1974, consumption is 22 $\times$ 10^6 Btu/yr higher than that for more recently built homes.

- This study clearly establishes the importance of household structure in influencing the level of household energy consumption. On the average, each addition to the number of household members increases energy consumption by 10^7 Btu/yr for the typical household.

TABLE S.1 Variable Sets and Elements

Variable Set	Elements
Economic	Household expenditures, electricity price, nonelectric energy price, consumer price index (excluding energy)
Weather	Heating degree days (HDD), 65°F base Cooling degree days (CDD), 65°F base HDD crossed with homes built before 1950 HDD crossed with homes built between 1950 and 1974 HDD crossed with electric space heating HDD crossed with heat-pump system CDD crossed with electric central air-conditioning
Household Structure	Number of household members Number of household members crossed with gender of household head Number of household members crossed with spouse's presence Number of household members crossed with age status of household head Number of household members who are children
End-Use	Electric water heating Electric cooking
Housing Type	Area of home Area of home crossed with number of rooms Area of home crossed with single-family, detached Area of home crossed with single-family, attached Area of home crossed with multifamily, fewer than five units

- The sex and age of the household head and the presence of the spouse are also influential in determining household energy consumption. Average annual household energy consumption increases by approximately 22×10^6 and 12×10^6 Btu in households with female and elderly household heads, respectively.

- The presence of the household spouse has a positive effect on energy consumption. Annual energy consumption increases by 12×10^6 Btu, on the average, for the typical household when the spouse is present.

The numerical derivatives give an absolute measure of the responsiveness of energy consumption to a small change in the independent variable. In many circumstances, however, a measure of the relative responsiveness of energy consumption to a change in the independent variable is appropriate -- the energy consumption elasticity provides this measure. The following are some important findings concerning variable elasticity:

- The estimated energy consumption elasticity for each variable is inelastic (i.e., the percent change in energy consumption with respect to a percent change in the independent variable is less than one).

- The single-family, detached and heating-degree-days variables are estimated to have the largest energy consumption elasticities: 0.39 and 0.37, respectively.

- For each percent increase in the number of household members, energy consumption is estimated to increase by 0.275% (0.11% for female-headed households).

- The estimated price elasticities for energy demand are all negative and very small. The estimated non-energy price elasticity is the largest: -0.086. The total household energy-expenditure elasticity estimate is 0.17.

The findings of this study constitute an initial step toward an understanding of the relationships among variables affecting energy consumption within a properly specified theoretical context.

The value of being able to separate out the partial effects of different factors on energy consumption is clear. The formulation and evaluation of energy policy is greatly enhanced by the ability to show how different factors influence energy consumption and expenditures. Conceptually, the ability to measure the separate influences of variables on energy consumption allows the policymaker to better ascertain specific policy effects.

1 INTRODUCTION

Research in the area of residential energy demand has been extensive. A number of good research endeavors have been completed over the last 10 years (see EPRI 1982; Blattenberger et al. 1983; DOE 1983; Cowing and McFadden 1984; Dubin and McFadden 1984; DOE 1984; Morrisey 1984; Dubin 1985; Hamblin et al. 1986; Khazzoom 1986; and Baxter 1987). However -- with the exception of analysis done by DOE (1983) -- none of this research was concerned with the determination of the systematic importance of specific sets of variables on energy demand, nor was any of it done within the context of a well-structured theoretical framework, using what is perhaps the richest source of residential energy consumption data available in the United States -- the U.S. Department of Energy's Residential Energy Consumption Survey.

This study analyzes the relationships between residential energy consumption and a number of variables. The variables are grouped into five categories:

- Economic variables -- income and prices;
- Weather -- heating and cooling degree days;
- Household structure -- household members and household head type;
- End-use -- electric cooking and water heating; and
- Housing type -- home area and type of home.

The effects of these variables on energy consumption are statistically analyzed using the sums of squared residual statistics (see Amemiya 1985, pp. 261-262).

The influences of the variables named above on energy consumption are interrelated. For this reason, the analysis is performed within the context of a well-structured theoretical framework; such a framework must permit the clear determination of the influence of particular variables on energy consumption.

The theoretical structure used is standard neoclassical consumer behavior theory, with a complete demand system of equations derived from a constrained utility-maximization problem. The utility function is a modified version of the Stone-Geary utility function. It is assumed that the demand for energy and non-energy goods is separable; this allows for the construction of a multistage budgeting model, as shown in Figure 1.

Demand at each stage represents a solution to an income-constrained (expenditure-constrained) utility (subutility) maximization problem (see Deaton and Muellbauer 1980, pp. 122-126; Geary 1950-51; Klein and Rubin 1947-48; Samuelson 1947-48; Stone 1954). The demand equations are static and may be characterized as *conditional long-run* demand equations. This interpretation can be made because instantaneous adjustment to a new equilibrium when prices and income change is assumed.

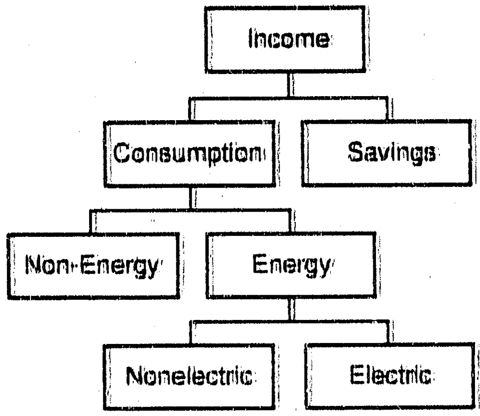

FIGURE 1 Multistage Budgeting Model

The second-stage utility equation (after income has been allocated between consumption and savings) is as follows:

$$u = \left(\frac{q_e}{\psi_e} - \gamma_e\right)^{\beta_e} (q_c - \gamma_c)^{1-\beta_e} \tag{1}$$

where:

u = consumption subutility function;

q_e = energy consumption (10^6 Btu/yr);

ψ_e = energy demand scale factor;

γ_e = nondiscretionary energy demand (10^6 Btu/yr);

β_e = marginal energy expenditure share;

q_c = non-energy consumption; and

γ_c = nondiscretionary non-energy demand.

If additional expenditures on energy and non-energy are to add up to total additional expenditures, the sum of the marginal expenditure shares must equal one. Therefore, one minus the marginal energy expenditure share, $1 - \beta_e$, is equal to the marginal non-energy expenditure share.

1.1 THE ENERGY DEMAND MODEL

Equation 1 is maximized subject to total expenditures. From the first-order conditions, the residential energy demand equation is derived:

$$q_e = (1 - \beta_e)\psi_e\gamma_e + \frac{\beta_e}{p_e}(m - p_c\gamma_c) \tag{2}$$

where:

p_e = price of energy ($/10^6$);

p_c = price index of non-energy goods; and

m = household expenditures ($/yr).

The energy demand scale factor (as well as the electricity demand scale factor, introduced below) plays an important role in the analysis: the effects of a number of different variable categories on energy consumption are measured through their influence on this factor.

The energy demand scale factor, ψ_e, is specified as an exponential function of its arguments:

$$\psi_e = \exp(\Sigma a_i x_i) \tag{3}$$

where a_i is the coefficient associated with the *ith* argument and x_i is the *ith* argument.

In effect, changes in an argument shift the energy demand curve either up or down, depending on whether the change has a positive or negative influence on the scale factor. Important goals in this analysis are the determination of the magnitude of these changes on energy consumption and their statistical significance.

As indicated in Figure 1, once energy expenditures are determined, they are allocated between electricity and nonelectric energy. At this level in the budgeting process, electricity demand is determined (and so is nonelectric demand, the difference between energy and electricity demand). The energy subutility function again takes the form of the modified Stone-Geary utility function:

$$u_e = \left(\frac{q_{el}}{\psi_{el}} - \gamma_{el}\right)^{\beta_{el}} \{q_{nel} - (\gamma_e - \gamma_{el})\}^{1-\beta_{el}} \tag{4}$$

where:

u_e = energy subutility function;

q_{el} = electricity consumption (10^6 Btu/yr);

ψ_{el} = electricity demand scale factor;

γ_e = nondiscretionary energy demand (10^6 Btu/yr);

γ_{el} = nondiscretionary electricity demand (10^6 Btu/yr);

β_{el} = marginal electricity expenditure share; and

q_{nel} = nonelectric energy consumption (10^6 Btu/yr).

Note that nondiscretionary demand for nonelectric energy is defined as the difference between the nondiscretionary demands for residential energy (also included in Eq. 2) and electricity.

1.2 THE ELECTRICITY DEMAND MODEL

The electricity demand equation is the solution of the maximization of the energy subutility function, Eq. 4, subject to total energy expenditures. Its functional form, as is expected, is very similar to the energy demand equation:

$$q_{el} = (1 - \beta_{el})\psi_{el}\gamma_{el} + \frac{\beta_{el}}{p_{el}} \{m_e - p_{nel}(\gamma_e - \gamma_{el})\} \tag{5}$$

where:

p_{el} = price of electricity ($\$/10^6$);

p_{nel} = price of nonelectric energy ($\$/10^6$); and

m_e = household energy expenditures ($/yr).

Just as the sum of the marginal expenditure shares on energy and non-energy had to equal one, so the sum of the marginal *energy* expenditure share on electricity and nonelectric energy must also equal one. Consequently, one minus the marginal electricity expenditure share, $1 - \beta_{el}$, is equal to the marginal nonelectric energy expenditure share.

Electricity demand also has associated with it a scale factor, ψ_{el}, that is functionally the same as the energy scale factor. The set of arguments associated with ψ_{el}, however, is different. Mathematically, this electricity scale factor is given by the following:

$$\psi_{el} = \exp(\Sigma b_j z_j) \qquad (6)$$

where b_j is the coefficient associated with the *j*th argument and z_j is the *j*th argument.

The relationship between the electricity scale factor and electricity demand is the same as that between the energy scale factor and energy demand: the electricity demand curve will shift up or down, depending on whether the factor's argument increases or decreases the value of the scale factor.

1.3 THE ANALYTICAL MODEL

The energy and electricity demand models, Eqs. 2 and 5, form the backbone of the analytical framework within which the relationship among variables and energy consumption is investigated. However, these two equations do not complete our system of relationships. Clearly, if the price of energy, p_e, and total residential energy expenditures, m_e, are considered, both of these variables must be endogenously determined.

The relationship between the consumption of electricity and nonelectric energy is determined by the level of energy expenditures, m_e, and the prices of electricity and nonelectric energy. In turn, energy expenditures are determined by energy consumption and the price of energy, p_e, which is the weighted average of the prices of electricity and nonelectric energy. The weights used in the calculation of the price of energy are the consumption fractions of electricity and nonelectric energy. Therefore, energy expenditures and the price of energ_ are unknowns and must be determined within the equation system.

Currently, there are only two equations specified in the analytical model: Eqs. 2 and 5 for energy and electricity consumption, respectively. There are, however, four unknowns: energy consumption, electricity consumption, energy price, and energy expenditures. In order to make the system complete or determinant, two additional equations must be specified. They are the following identities:

$$p_e \equiv \frac{(p_{el}q_{el} + p_{nel}q_{nel})}{q_e} \qquad (7)$$

where:

p_e = price of residential energy ($/$10^6$ Btu);

p_{el} = price of electricity ($/$10^6$ Btu);

p_{nel} = price of nonelectric energy ($/$10^6$ Btu);

q_{el} = electricity consumption (10^6 Btu/yr);

q_{nel} = nonelectric energy consumption (10^6 Btu/yr); and

q_e = residential energy consumption (10^6 Btu/yr);

and

$$m_e \equiv p_e q_e \tag{8}$$

where m_e = residential energy expenditures ($/yr).

Equations 2, 5, 7, and 8 constitute the complete analytical framework within which the effects of economic, weather, household-structure, end-use, and housing-type variables on energy consumption are assessed. These equations form a system of nonlinear equations that are most easily solved by using nonlinear estimation techniques (see Amemiya 1985, pp. 245-265).

2 METHOD OF ANALYSIS

An analysis of residential energy end-use patterns and expenditures requires the simultaneous determination of a number of different phenomena. The level and cost of energy consumption are determined both by the energy mix (i.e., the electricity fraction of total energy use) and by many other, exogenous factors (i.e., economics, weather, house age, housing type, and household structure). Under these circumstances, where there are a number of dependent variables and numerous independent ones, multivariate analysis can be valuable.

For the sake of clear exposition of the analysis, it must be framed within a theoretical context. For this reason, the standard consumer behavior paradigm — consumers maximize their utility subject to an expenditure constraint – is embraced. One justification for the use of this model is that it avoids anomalous expenditure behavior in the face of changes in income and prices. The model also allows for the consistent integration of other exogenous variables (in addition to expenditure and prices) that affect energy consumption.

2.1 INCORPORATION OF VARIABLES INTO MODEL

The theoretical model is described in Section 1. As was noted earlier, the model is a variant of Stone's linear expenditure systems model, in which a scale factor has been introduced; through the scale factor, variables other than price and income are incorporated into the model.

Variables associated with the five variable sets described earlier are added sequentially. The statistical significance of the additional variables is determined through the change in the sums of the squared residuals.

The test statistic used to determine significance is the difference between the constrained and the unconstrained sums of squared residuals (denoted SSRD):

$$\mathrm{SSRD} = \frac{T}{S_T(\hat{\alpha})}[S_T(\tilde{\alpha}) - S_T(\hat{\alpha})] \tag{9}$$

where:

S_T = sum of squared residuals;

T = sample size;

$\hat{\alpha}$ = $(k + q) \times 1$ vector of parameter estimates connected with the unconstrained model; and

$\tilde{\alpha}$ = $k \times 1$ vector of parameter estimates connected with the constrained model.

The sum of squared residuals* is expressed as follows:

$$S_T = r'[\hat{\Sigma}^{-1} \otimes W(W'W)^{-1}W']r \qquad (10)$$

where:

r = 4T × 1 vector of residuals for four equations over T observations;

$\hat{\Sigma}$ = consistent estimate of the unknown disturbance term's variance-covariance matrix;

$\otimes$ = Kronecker product; and

W = n × p matrix of variable instruments.

The number of instruments, p, is equal to or greater than the number of explanatory variables, k + q, specified in the unconstrained model.

In testing the statistical significance of each variable classification, sets of variables are sequentially added to the model. The newly specified model is defined as the unconstrained model and the previously calculated model as the constrained model. The SSRD is then calculated by using the sums of squared residuals for the two models.

The SSRD statistic is asymptotically distributed as chi-square with q (the number of variables added to the unconstrained model) degrees of freedom. Therefore, the overall test for statistical significance of the newly specified model can be performed by using the chi-square table.

2.2 DATA USED IN ANALYSIS

The data used for this analysis are provided by the Energy Information Administration (EIA), U.S. Department of Energy (DOE). The EIA has collected residential energy consumption data since 1978. Currently, there are seven EIA residential energy consumption data files. The first two surveys were precursors to the Residential Energy Consumption Surveys (RECS) used in this analysis: the first survey, called the National Interim Energy Consumption Survey (NIECS), covered the period from April 1978 to March 1979 (DOE 1980), and the second survey, called the Residential Energy Consumption Survey Household Screener Survey (Screener), covered the period from April 1979 to March 1980 (DOE 1981).

There are now five RECS data files, which cover the April 1980 to December 1987 period (DOE 1982, 1983a, 1985, 1987a, and 1989). These five data files were pooled to produce a data

*The value calculated in Eq. 10 is not, technically, the sum of squared residuals. The actual value would be the simple cross product of the residuals (r'r), and the term in brackets would not be included in its calculation. However, because a full-information procedure is being used to develop the model estimates, a modified version of the standard SSRD test is being used.

set containing nearly 27,000 observations. Only one-third of these observations were used to obtain the model estimates described earlier, because the computer time required by the method used to solve the system of nonlinear equations (consisting of Eqs. 2, 5, 7, and 8) made the use of all the available observations prohibitive.

Technical questions on sampling design are answered in the appendixes of various EIA reports (see DOE 1983b, 1983c, 1984a, 1987b, and 1990).

3 RESULTS

The analytical model represented by Eqs. 2, 5, 7, and 8 was approximately solved by using the SAS Institute's three-stage nonlinear procedure (SAS Institute 1984, pp. 505-550). The procedure was used to obtain estimated values for five models, where variables falling in the five variable-set categories -- economic, weather, household-structure, end-use, and housing-type variables -- were added sequentially. The variables included in each category are listed in Table 1.

Table 2 lists the estimated parameters and gives their definitions. Table 3 gives the estimated parameter values for each of the five variable sets.

3.1 SIGNIFICANCE OF PARAMETERS

With the exception of the number-of-children (a_0) and the heat-pump (b_2) variables, each parameter estimate is statistically significant at the 0.05 level. As shown in Table 4, the value of the unexplained variance for the entire system declines dramatically with the addition of each successive set of variables.

In Table 3, the goodness-of-fit measure declines for both the energy and electricity demand equations in the housing-type model, but the sum of the system's squared residuals declines. Only Eqs. 2 and 5 have parameters that are estimated, while Eqs. 7 and 8 are identities that contain no parameters. The implication of this is that the addition of the housing-type variables to the model improves its value for explaining variations in energy price and/or energy expenditures.

Each set of variables added to the analytical model is statistically significant at the 0.01 level. Therefore, for the data sample used to conduct this analysis, each set of variables -- economic, weather, household-structure, end-use, and housing type -- contributes significantly to explaining variations in the model's dependent variables.

3.2 NUMERICAL ANALYSIS

In this section, the estimates obtained from the housing-type model are used to calculate a number of numerical derivatives and energy-consumption elasticities (the percent change in energy consumption as a result of a percent change in a predetermined variable). The derivatives and elasticity estimates are calculated using the 1987 mean values of the exogenous variables (DOE 1989).

The elasticities are used to estimate the contribution of various factors to changes in energy consumption between the 1984-85 and 1987 RECS survey periods. In Table 5, energy consumption and some important explanatory variables are shown for 1984-85 and 1987.

The variables listed in Table 5 are assumed to condition energy consumption in a fashion somewhat similar to the way changes in income do: by causing shifts in the energy demand curve. Along with the effects of these conditioning factors, energy consumption is also

TABLE 1 Elements of Variable Sets

Variable Set	Elements
Economic	Household expenditures, electricity price, nonelectric energy price, consumer price index (excluding energy)
Weather	Heating degree days (HDD), 65°F base Cooling degree days, (CDD), 65°F base HDD crossed with homes built before 1950 HDD crossed with homes built between 1950 and 1974 HDD crossed with electric space heating HDD crossed with heat-pump system CDD crossed with electric central air conditioning
Household Structure	Number of household members Number of household members crossed with gender of household head Number of household members crossed with spouse's presence Number of household members crossed with age status of household head Number of household members who are children
End-Use	Electric water heating Electric cooking
Housing Type	Area of home Area of home crossed with number of rooms Area of home crossed with single-family, detached Area of home crossed with single-family, attached Area of home crossed with multifamily, fewer than five units

affected by changes in economic variables -- prices and income. In Table 6, changes in economic variables between periods are shown.

Between these two periods (1984-85 and 1987), total residential energy consumption declined by about 1.64%. Changes also occurred in key variables that affect energy consumption. What is of interest is the relative importance of these variable changes with respect to energy consumption. Estimates of these relative effects can be determined by using the numerical derivatives for the equation system comprising Eqs. 2, 5, 7, and 8.

In Table 7, the estimated numerical derivatives -- the partial change in energy consumption with respect to a small change in some explanatory variable -- of a number of scale variables are shown. The variables in the table are of both the continuous and the nominal types. With the exception of home area, the effects exerted by these variables on total energy consumption are consistent with initial expectations.

TABLE 2 Parameters and Their Definitions

Model	Parameter	Definition
Energy Demand		
	β'_{0}	Marginal residential energy share of total expenditures
	γ_{0}	Nondiscretionary residential energy demand
	a_1	Heating degree days (65°F base)
	a_2	Heating degree days crossed with homes built before 1950
	a_3	Heating degree days crossed with homes built between 1950 and 1974
	a_4	Cooling degree days (65°F base)
	a_5	Number of household members
	a_6	Number of household members crossed with female-headed household
	a_7	Number of household members crossed with a household in which the spouse is present
	a_8	Number of household members crossed with a household where the head is 65 years old or older
	a_9	Number of household members who are less than 18 years old
	a_{10}	Total home area (square feet)
	a_{11}	Total home area crossed with number of rooms
	a_{12}	Total home area crossed with single-family, detached home
	a_{13}	Total home area crossed with single-family, attached home
	a_{14}	Total home area crossed with multifamily housing with fewer than four units
Electricity Demand		
	β'_{el}	Marginal electricity share of total energy expenditures
	γ_{el}	Nondiscretionary electricity demand
	b_1	Heating degree days crossed with electric space heating
	b_2	Heating degree days crossed with heat-pump system
	b_3	Cooling degree days crossed with electric central air-conditioning
	b_4	Electric water heating
	b_5	Electric cooking

On closer inspection, the negative relationship between energy consumption and home area is not completely surprising. Home area includes both heated and unheated areas within the home. It is therefore likely that the negative relationship between home area and energy consumption reflects the increase in unheated space, such as garages and attics. Given that the heated area remains constant, an increase in home area is likely to reduce energy consumption because of the insulating properties of the additional, unheated space.

At the mean level of energy consumption -- about 102×10^6 Btu -- the relative differences in energy consumption are dramatic when one compares older homes with newer ones, and single-family and small multifamily units (fewer than five units) with other housing types (such as mobile homes and multifamily homes with five units or more). The numerical derivatives indicate that energy consumption increases in the range of about 20 to 30% for homes

TABLE 3 Parameter Estimates for Energy and Electricity Models

Model	Parameter	Economic	Weather	Household Structure	End-Use	Housing Type
Energy Demand						
	β'_0	0.00946	0.01078	0.01132	0.01133	0.00825
		(0.00034)	(0.00034)	(0.00034)	(0.00035)	(0.0004)
	γ_0	89.50	42.05	33.92	37.56	42.75
		(0.72610)	(1.33)	(1.15)	(1.24)	(1.42)
	a_1	-	6.54E-05	5.37E-05	3.9E-05	4.34E-05
		-	(6.2E-06)	(6E-06)	(6.1E-06)	(5.9E-06)
	a_2	-	8.3E-05	7.6E-05	8.28E-05	6.55E-05
		-	(5.1E-06)	(4.9E-06)	(5E-06)	(4.8E-06)
	a_3	-	6.38E-05	5.67E-05	6.22E-05	5.39E-05
		-	(5.3E-06)	(4.9E-06)	(5.1E-06)	(4.8E-06)
	a_4	-	0.00017	0.00016	0.00011	0.000108
		-	(1.1E-05)	(1.1E-05)	(1.1E-05)	(1.1E-05)
	a_5	-	-	0.03890	0.03362	0.02987
		-	-	(0.01411)	(0.01406)	(0.01368)
	a_6	-	-	0.09606	0.09807	0.08872
		-	-	(0.01448)	(0.01441)	(0.01396)
	a_7	-	-	0.06684	0.06677	0.04463
		-	-	(0.01345)	(0.01339)	(0.01283)
	a_8	-	-	0.08256	0.08098	0.04975
		-	-	(0.00667)	(0.00669)	(0.007)
	a_9	-	-	0.00224	0.00228	0.00138
		-	-	(0.0016)	(0.00159)	(0.00162)
	a_{10}	-	-	-	-	-5.14E-04
		-	-	-	-	(3.8E-05)
	a_{11}	-	-	-	-	2.38E-05
		-	-	-	-	(1.1E-06)
	a_{12}	-	-	-	-	0.0004
		-	-	-	-	(0.00004)
	a_{13}	-	-	-	-	0.00037
		-	-	-	-	(3.9E-05)
	a_{14}	-	-	-	-	0.00036
		-	-	-	-	(4.1E-05)
	R-Square	0.0521	0.2049	0.2737	0.2774	0.2635
Electricity Demand						
	β_{0l}	0.75862	0.51332	0.50396	0.5170	0.50237
		(0.00936)	(0.007)	(0.00684)	(0.00648)	(0.00654)
	γ_{0l}	37.09	11.92	10.34	4.89	6.71
		(0.45313)	(0.4562)	(0.41873)	(0.44399)	(0.46151)
	b_1	-	0.00028	0.00029	0.00016	0.00016
		-	(6.1E-06)	(6.5E-06)	(4.2E-06)	(4E-06)
	b_2	-	7.8E-06	1.01E-05	7.07E-06	5.97E-06
		-	(5.5E-06)	(5.6E-06)	(4.9E-06)	(4.7E-06)
	b_3	-	0.00041	0.000435	0.00025	0.00024
		-	(1.2E-05)	(1.2E-05)	(8.4E-06)	(7.9E-06)

TABLE 3 (Cont'd)

Model	Parameter	Economic	Weather	Household Structure	End-Use	Housing Type
	b_4	-	-	-	1.11557	0.99218
		-	-	-	(0.05492)	(0.04418)
	b_5	-	-	-	0.64405	0.50179
		-	-	-	(0.0646)	(0.04884)
System Statistics	R-Square	0.2792	0.6747	0.6809	0.7405	0.7397
	Sample Size	8877	8877	8877	8877	8877
	Objective	1.10999	0.89110	0.80893	0.71028	0.58496

[a]Notation used for brevity in dealing with very small values: 6.54E-05 = 6.54 × 10^{-5}.

TABLE 4 Analysis of Variance

Variable Set Added to Model	Sum of Squared Residuals	Difference in Sums of Squared Residuals[a]	Degrees of Freedom	SSRD Statistic
Economic	9853	-	-	-
Weather	7911	1942	7	2179
Household Structure	7181	730	5	902
End-Use	6305	876	2	1233
Housing Type	5193	1112	5	1901

[a]Immediately preceding value of squared residual minus present value.

built before 1974, compared with homes built in 1974 and after; energy consumption increases by about 55 to 65% for single-family (detached and attached) and small multifamily structures (fewer than five units), compared with other housing types.

At the mean level of energy consumption, space conditioning requirements also account for substantial amounts of energy consumed in the residential sector. Space heating accounts for about 35 to 40% of the energy consumed by households, and cooling for about 10 to 15%.

Household-structure variables also have a considerable influence on energy consumption. Empirically, the analysis indicates that, at the mean consumption level, energy consumption increases by about 10% with each additional household member.

In cases where the household head is female or elderly, or where the spouse is present, the impact on energy consumption is positive. Energy consumption increases for female-headed households by approximately 20 to 25% compared with male-headed households. For

TABLE 5 Changes in Energy Consumption and Related Variables between 1984-85 and 1987

Variable	Value[a] 1984-85	1987	Change (%)
Energy Consumption per Household (10^6 Btu/yr)			
Total energy[b]	103.5	101.8	-1.64
Electricity	28.88	29.3	1.45
Weather (65°F base)			
Heating degree days	4620	4440	-3.90
Cooling degree days	1060	1260	18.87
Household Structure			
Household members	2.7	2.65	-1.85
Spouse present (%)	59.9	58.0	-3.17
Head of household (%)			
Single female	26.85	27.85	3.72
Elderly person	25.6	29.5	15.23
Home Age (%)			
Home built before 1950	37.0	35.0	-5.41
Home built during 1950-1974	46.6	44.2	-5.15
Home built after 1974	16.4	20.8	26.83
Housing Type (%)			
Single-family, detached	63.1	62.0	-1.74
Single-family, attached	4.65	5.3	13.98
Multifamily, <5 units	11.8	11.35	-3.81
Other	20.4	21.9	7.35

[a]The values shown in this table are moving averages between survey periods, with the 1984-85 value equal to the average of the values given in RECS3 (DOE 1985) and RECS4 (DOE 1987a) and the 1987 value equal to the average of the RECS4 and RECS5 (DOE 1989) values.

[b]Total energy consumption is equal to the sum of electricity, natural gas, fuel oil/kerosene, and liquefied petroleum gas consumption.

Sources: DOE 1987a and 1989.

TABLE 6 Changes in Prices and Household Expenditures between 1984-85 and 1987

Variables	Value		Change (%)
	1984-85	1987	
Household Income ($/yr)[a]	23,290	26,925	15.61
Household Expenditures ($/yr)[b]	17,420	19,800	13.66
Electricity Price ($/$10^6$ Btu)[a]	20.90	22.14	5.93
Nonelectric Energy Price ($/$10^6$ Btu)[a]	6.42	6.06	-5.61
Consumer Price Index, 1979 base[c]	1.380	1.497	8.48
Non-Energy Price Index, 1979 base[c]	1.351	1.494	10.58

[a]Sources: DOE 1987 and 1989.

[b]Household expenditures are derived from household income information in DOE surveys (DOE 1987a and 1989). Household expenditures are assumed to be a function of household income, consumer prices, and age of household head. An equation reflecting these relationships is used to calculate household expenditures.

[c]Sources: U.S. Department of Labor (DOL) 1985 and 1988.

TABLE 7 Estimated Changes in Energy Consumption as a Function of Changes in Selected Independent Variables

Variable	Change in Consumption, Numerical Derivative (10^6 Btu)	Variable	Change in Consumption, Numerical Derivative (10^6 Btu)
Weather, 65°F Base		Number of Rooms	3.79
Heating degree days[a]	37.3	Home Area (ft^2)[c]	-1.32
Cooling degree days[b]	12.2	Household Members	10.42
		Spouse Present	11.09
Home Age			
Built before 1950	27.27	Head of Household	
Built during 1950-74	22.44	Single female	22.04
		Elderly person	12.36
Housing Type			
Single-family, detached	63.39		
Single-family, attached	58.75		
Multifamily, <5 units	57.81		

[a]Measures change in energy consumption given an increase of 4400 in HDD.

[b]Measures change in energy consumption given an increase of 1260 in CDD.

[c]Measures change in energy consumption given a 10% increase (170 ft^2) in home's area.

households where the spouse is present or where the household's head is an elderly person (65 years or older), energy consumption increases by about 10 to 15% compared with households where the spouse is not present or the head is under 65 years old.

3.3 RELATIVE SENSITIVITIES TO VARIABLES

The derivatives presented in Table 7 indicate how energy consumption changes in absolute terms. However, these derivatives do not reflect the relative sensitivity of energy consumption with respect to the various independent variables. For a better understanding of the relative relationship, estimates of the elasticities at the means were calculated.*

In Table 8, energy demand elasticities are presented for a number of important explanatory variables. Along with the elasticities, the percentage changes for each variable, given in Tables 5 and 6, are again shown. The product of the variable elasticity -- the percent change in energy consumption given a percent change in the variable value -- and the percent change in the explanatory variable gives an estimate of the percent change in energy consumption attributable to the change in the explanatory variable.

*Technically, the elasticities should be calculated by using a weighted average of the numerical derivatives calculated at the household level, since the assumptions for an exact nonlinear aggregation condition are not satisfied.

TABLE 8 Changes in Energy Demand Elasticities and Effects on Energy Consumption

Variable	Elasticity	Change, 1984-85 to 1987 (%)	Effect on Energy Consumption (%)
Weather, 65°F Base			
Heating degree days	0.371	-3.90	-1.45
Cooling degree days	0.121	18.87	2.28
Home Age			
Built before 1950	0.095	-5.41	-0.51
Built during 1950-74	0.097	-5.15	-0.50
Housing Type			
Single-family, detached	0.387	-1.74	-0.67
Single-family, attached	0.031	13.98	0.43
Multifamily, <5 units	0.066	-3.81	-0.25
Household Members	0.275	-1.85	-0.51
Spouse Present	0.064	-3.17	-0.20
Head of Household			
Single female	0.110	3.72	0.41
Elderly person	0.027	15.23	0.41
Electricity Price	-0.042	5.93	-0.25
Nonelectric Energy Price	-0.038	-5.61	0.21
Non-Energy Price Index	-0.086	10.58	-0.91
Household Expenditures	0.166	13.66	2.27

Here, the demand system can be characterized as a conditional long-run model. Therefore, the changes in energy consumption due to changes in the scale factor, ψ_0, represent shifts in the long-run energy demand curve. The expenditure and price elasticities represent conditional long-run elasticities: elasticities conditional on the household's weather, structure, age, and housing-type profile.

The sum of the estimated changes in energy consumption due to variations in all the variables is 0.54% (energy consumption is estimated to increase by 0.54%), compared with the 1.64% decline in energy consumption shown in Table 5. After the price and income values are excluded, the sum falls to -0.57%. The difference in the estimated effect, obtained by using population averages, is not surprising. It is likely that the use of population averages results in biasing of the calculated effects.*

Although the derivatives estimated at the means do not give unbiased estimates of aggregate effects, they are still illustrative. The variables with the largest estimated elasticities are "single-family, detached" and "heating degree days," with "number of household members" a close third.

Because of their relative volatility, heating and cooling degree days and household expenditures are expected to make the largest periodic contributions to energy consumption changes. Over the long run, housing-stock-related variables, such as housing-stock age and housing type, can also contribute substantially to energy consumption changes. For example, a change in the relative number of single-family, detached homes would affect energy consumption dramatically.

*As indicated earlier, the estimates obtained with the model described in this report are calculated by using household data. Because of this, the calculation of the effect of changing variables on energy consumption should be done at the household level. The effects should then be aggregated over all households to determine the average population effects (using household energy consumption to weight the results).

4 CONCLUSIONS

In order to understand the ramifications of energy policy, knowledge of the relationship between energy consumption and other variables affecting energy consumption is required. The purpose of the research described in this report is to quantify the connection between a number of these variables and energy consumption. The research findings provide a basis for understanding the relative influence of various factors on energy consumption. Consequently, the potential effect of policy on energy consumption and expenditures can be more clearly understood. The variables have been grouped into five categories: economic, weather, household-structure, end-use, and housing-type variables. The variable parameters in each category are listed in Table 2 (see Section 3).

Statistically, each of the variable categories has proved to be significant. The individual parameter estimates, with the exception of the coefficients for heat-pump variable and number-of-children variables, were all statistically significant.

In calculating the numerical derivatives and elasticities, mean values of the explanatory variables were used. The estimated partial effects using this procedure are certainly biased. In order to obtain unbiased population estimates, these calculations, in the future, should be done at the household level. The household estimates would then be aggregated to obtain the population estimates.

4.1 ECONOMIC VARIABLES

The parameters capturing the influence of household expenditures and prices on energy consumption are all statistically significant. The estimated elasticities indicate the demand (conditional) for energy is very price-inelastic. The expenditure elasticity – which is also very inelastic –is four times as large as the absolute values of the electricity price and nonelectric energy price elasticities, and it is twice as large as the non-energy price elasticity.

The implication of this result is that total energy consumption is relatively more sensitive to income changes than it is to price changes. The inelastic expenditure elasticity implies that the energy-expenditure share declines as total expenditures increase. This result is clearly borne out by both time-series and cross-sectional data analysis.

These findings are highly relevant to the formulation and evaluation of policy. They imply that market-based policy, which has the objective of reducing energy consumption through the upgrading of existing housing stock and appliances, will be only moderately successful.

4.2 WEATHER VARIABLES

Heating and cooling degree days are important variables in explaining variations in household energy consumption. The heating-degree-day (HDD) variable has the largest elasticity of all the continuous variables specified in the energy demand model. Changes in residential energy consumption (at the point of end-use) over the past two decades probably have been, in large part, the result of population migration from the Northeast and Midwest to the South and West Census regions.

The model values also indicate that declining energy consumption due to decreasing heating loads has been partially offset by increasing cooling loads. In particular, population increases in the South have probably led to increased energy consumption associated with space-cooling requirements.

4.3 HOUSEHOLD-STRUCTURE VARIABLES

The household-structure variables are statistically significant in their relationship with energy consumption. The relationship between household structure and energy consumption is based on the reasonable hypothesis that household structure, through its association with home utilization, will affect energy consumption.

The supposition is advanced that home occupancy (utilization) and the number of household members are directly related. Because of this, the level of residential energy consumption is expected to increase with an increase in the number of household members.

In fact, the household-member variable turns out to be extremely important. Next to the heating-degree-day variable, the number of household members has the largest elasticity of all the continuous variables specified in the model. In the short run, however, the effect of changes in the number of household members on energy consumption is anticipated to be rather small, since the number of household members changes only slightly from year to year. In the long run, the net effect of the number of household members on energy consumption has been negative because of the decline in the average number of household members.

A number of other interesting relationships with energy consumption emerge after other variables have been overlaid on top of the household-member variable. These relationships are also potentially relevant to policy formulation and assessment. The model demonstrates that a single-female-headed household will consume more energy than a male-headed household. It is speculated that, because of the higher rate of unemployment for a typical single female head, the single-female-headed home will have a higher occupancy rate. As a result of this higher occupancy rate, energy consumption will also be higher.

Rate of home occupancy may also be important in the cases of households with elderly heads and where the spouse is present. In both these circumstances, it is speculated that the rate of home occupancy will be higher, and consequently, so will the amount of energy consumed. These hypotheses are borne out by the model.

4.4 HOUSING-TYPE AND HOME-AGE VARIABLES

For a number of categorical variables, the effect on energy consumption is substantial. Living in a single-family home (attached or detached) or in a small multifamily dwelling (fewer than five units) adds substantially to the amount of energy consumed. Also, as would be expected, living in an older home adds to the amount of energy consumed.

The increase in household energy consumption for single-family and small multifamily dwellings is estimated to be about 60×10^6 Btu/yr compared with the average level of energy consumption for other types of homes (larger multifamily dwellings and mobile homes). For homes built before 1974, household energy consumption is estimated to be about 25×10^6 Btu/yr more compared with average energy consumption for homes built after 1974.

On the average, the energy-consumption elasticity associated with single-family, detached homes is the largest of all the variables specified in the demand model. However, because of the rather slow rate of turnover in housing stock, the effect of changes in these variables on energy consumption will only be felt in the long term.

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