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I. Introduction

The 1970's and early 1980's were characterized by unparalleled changes in the world's energy markets. During this time, the Organization of Petroleum Exporting Countries (OPEC) engineered two drastic increases in the price of petroleum. Energy consumers faced natural gas curtailments, gasoline and heating oil shortages, and both oil and natural gas price deregulation. Energy prices, which had been stable and low, became volatile with rapid changes in relative and absolute fuel costs.

These radical changes in energy prices -- relative to other goods and to each other -- would be expected to generate significant changes in the energy consumption patterns and the underlying energy demand functions of residential consumers. In response, demand functions are now likely to be more responsive to both changes in the level of fuel prices and to changes in relative fuel prices.

The paper focuses on the demand for electricity, petroleum, and natural gas and tests for structural change in the demand for these major energy sources. A partial adjustment model is estimated for each fuel during two different periods, 1971-74 and 1979-82. Pooled time series methods are used on state-level data.

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* Federal Reserve Bank of Dallas. The views expressed are those of the authors and do not necessarily reflect official views of the Federal Reserve Bank of Dallas or the Federal Reserve System.

Based on the estimates, structural change appears to have occurred in electricity and petroleum consumption, but not in the demand for natural gas. In the electricity and petroleum demand equations, the speed with which consumers adjust to shocks in exogenous variables increases in the post-1979 period, with price elasticities also increased in absolute value. In contrast, the changes in the natural gas parameters were minor and the differences were not sufficient to reject the hypothesis of no structural change.

Also of interest, the variance of the estimate appears to have increased in the later period in all fuel demand equations. Consequently, tests of structural change require proper correction for changes in the variance-covariance matrix in the different time periods.

Comparing fuels, the largest changes in own and cross-price elasticities were found for petroleum. Furthermore, judging from the increase in the natural gas cross-price elasticities in the electricity and petroleum equations, there appears to be enhanced substitutability of natural gas for those fuels.

The paper is organized in the following way. The model of energy demand is developed in Section II. Data used to estimate the model is then described in Section III, along with a comparison to data used in other studies. Pooled estimates and tests for structural change are then presented in Section IV, with conclusions discussed in Section V.

II. A Model of the Residential Sector's Demand for Energy

In virtually all instances, the residential sector's demand for energy is derived from its use in producing different services, such as space heating and cooking. As such, the demand for energy by the residential sector is dependent on the stock of energy-using capital goods. An analysis of the residential demand for energy must deal with adjustments in the households' stock of capital goods in response to changes in the variables that affect energy demand.

In the short run, the stock of capital goods in the household is fixed, only the intensity of use of the capital good is variable (i.e., a thermostat can be turned down). The short-run demand for energy is then decided by the contemporaneous values of variables that determine the intensity with which the capital goods are used, such as price, weather, and income. In the long run, consumers can also vary their stock of capital goods, although full adjustment may require a considerable length of time.

One method to account for both the short run and long run responses is to explicitly model the capital stock and subsequent changes. [Garbacz (1983)]. Such an approach, however, requires extensive data on household appliances, which is available only on a limited basis. Recognizing the data limitations, researchers have favored the use of partial adjustment models to implicitly capture the capital stock adjustment process.[1/]

The partial adjustment model begins with a static equilibrium model:

(1) $$Q^*_{ijt}=f_{K^*}(P_{ijt},Z_{jt})$$

where Q^*_{ijt} is the desired demand for a particular fuel, P_{ijt} is the average price of that fuel, Z denotes a vector of other variables, such as income and heating and cooling days, that may influence energy demand, and where the subscripts, i, j, and t, refer to the fuel, individual, and time period, respectively. The function, $f_{K^*}(.)$, specifies the desired level of fuel consumption if the capital stock was the optimal capital stock given P_{ijt} and Z_{jt}.

When P_{ijt} and Z_{jt} change in such a way as to make the short-run capital stock deviate from the long-run desired capital stock, desired and actual consumption will differ. Over time, consumers will adjust their capital stock to bring actual consumption into line with desired levels, but in the short term the static equilibrium will not be achieved. To model this dynamic process we use a partial adjustment model:

$$(2) \qquad Q_{ijt} = (1-\lambda)Q_{ijt-1} + \lambda Q^*_{ijt},$$

where Q_{ijt} is the actual demand for the fuel and λ is the factor defining the speed with which actual demand adjusts to desired levels through the implicit adjustment in the capital stock from what was previously optimal to what is optimal under the new realizations of the independent variables. Normally, we assume that λ takes on values between 0 and 1, where 0 implies no adjustment and 1 implies instantaneous adjustment. Incorporating the partial adjustment process into (1) and linearizing $f_{K^*}(P_{ijt}, Z_{jt})$ yields a demand equation in an estimable form:

(3) $$Q_{ijt} = (1-\lambda)Q_{ijt-1} + \lambda[\alpha_1 P_{ijt} + \alpha_2 Z_{jt}].$$

Short run effects of independent variables are measured by the parameter estimates on P_{ij} and Z_j yielded in a linear regression, while the long term effects are derived by dividing those linear parameter estimates for P_{ij} and Z_j by the parameter estimate on the lagged dependent variable. The model, therefore, differentiates between the short and long term effects, even though there are no explicit estimates of the capital stock or the intensity of the use of capital.

III. Data and Estimation

Three demand equations were estimated for residential energy consumption:

(4) $$ELEC_{jt} = a_{10} + a_{11}ELEC_{jt-1} + a_{12}PRELEC_{jt} + a_{13}PRGAS_{jt} + a_{14}HEAT_{jt} + a_{15}COOL_{jt} + \varepsilon_{Ejt},$$

(5) $$NGAS_{jt} = a_{20} + a_{21}NGAS_{jt-1} + a_{22}PRGAS_{jt} + a_{23}PRELEC_{jt} + a_{24}HEAT_{jt} + \varepsilon_{Gjt},$$

(6) $$PETR_{jt} = a_{30} + a_{31}PETR_{jt-1} + a_{32}PRPETR_{jt} + a_{33}PRGAS_{jt} + a_{34}HEAT_{jt} + \varepsilon_{Pjt},$$

where ELEC is per capita electricity consumption in state j,

NATG is per capita natural gas consumption in state j,

PETR is per capita petroleum consumption in state j, PRELEC is the price of electricity in state j,

PRGAS is the price of natural gas in state j,

PRPETR is the price of petroleum in state j,

HEAT is the reported heating degree days for state j, and

COOL is the reported cooling degree days for state j.

All fuels are measured in millions of BTUs, with fuel prices expressed in 1967 dollars/MMBTU after being deflated by the non-fuel consumer price index. The energy consumption and price data for each state came from the U.S. Department of Energy's State Energy Data System, covering the years 1970-82. All variables other than heating and cooling degree days are estimated in logarithmic form.

The models represented by equations (4) - (6) have some important differences from many other studies of residential energy consumption. First, given the high degree of multicollinearity between fuel prices and the fact that fuels are often pair-wise competitive, rather than competitive between all fuels, the models include only the own-price variable and the fuel price of its major substitute. Consequently, the electricity demand equation has the prices of electricity and natural gas, the gas demand equation has the prices of natural gas and electricity, and the petroleum demand equation has the prices of petroleum and natural gas.

Second, heating and cooling data do not appear to have equally important effects on consumption across fuels. Both heating and cooling were found to be significant factors in explaining electricity demand, but cooling data was not important for natural gas or petroleum demand. Consequently, the final equations excluded cooling degree days from those equations.

Third, unlike most other studies of residential energy demand, per capita income was found to be unimportant as an explanatory variable. We attempted to estimate the effects of income in a variety of ways as suggested by Houthakker and Taylor (1966),[2/] but in no case was income significant. We did consider the possibility of a high degree of collinearity between income and other explanatory variables, but it is not present to a great degree. The lack of significance may appear surprising but it is not without precedent in energy demand studies [Beierlein, Dunn, and McConnon (1981); Houthakker (1980)].[3/]

The price and quantity data also differ from that used in other studies. Several advantages exist with the DOE data set in comparison with other data commonly used. First, a period of both decreasing and increasing real energy prices is included. The time series is long enough to allow for some adjustment to the significant price shocks experienced during the 1970's. Further, the data exhibits substantial price and consumption variability across individual states and over time, making the estimation of price coefficients in the model more precise. Another advantage of using this data set is that it allows for a more thorough investigation of the determinants of the residential demand for petroleum. Previously, data deficiencies have hampered efforts of researchers to obtain reliable estimates. Consequently, the DOE data set allows us to more accurately investigate hypotheses, such as the shift in residential demand for petroleum products due to fuel switching and conservation efforts.

Unfortunately, the DOE data set contains only average prices for fuels. Since the market for electricity, and to a certain extent that of natural gas, is characterized by multi-step pricing, where quantities are purchased in blocks at a decreasing marginal cost, Taylor (1975) has questioned the interpretation of price coefficients estimated from functions using average prices. Nevertheless, the use of average prices is fairly common.[4/]

IV. Estimation Results

Equations (4) - (6) were estimated separately using the pooled time series cross section data discussed in Section III. Tests were then performed to determine whether the coefficients in the structural equation changed between two time periods, 1971-74, and 1979-82.

Before testing for structural change in the coefficient vector, however, the model was tested for the presence of autocorrelation and for structural change in the variance covariance matrix. Because of the presence of the lagged dependent variable in the demand equations, it is necessary to test for the presence of autocorrelated disturbances to avoid inconsistent estimates. Given the small number of time period observations in each cross section, Durbin-h tests are generally neither feasible or reliable. Consequently, an assymptotically equivalent procedure described by Durbin (1970) was used. Ordinary least squares is estimated for each cross section. The residual from that regression is then regressed on its own lag and the full set of explanatory variables, with the coefficient on the lagged residual tested with a standard t-test. In only 3 out of 144 cases (only lower-48 states were used in this study) was the presence of autocorrelation indicated, making the assumption of no autocorrelation more plausible.

Folowing the literature [Balestra and Nerlove (1966), Beierlein, Dunn, and McConnon (1981), and Houthakker, Verleger, and Sheehan (1974)], the error components estimation method is used in this study. By taking into account both the differences between states and those differences arising over time, parameter estimates are more efficiently estimated than would be the case with ordinary least squares.[5/]

Testing for structural change in the parameters required correction for changes in the error structure in the two periods. The estimated variances associated with time, cross-section, and residual error from the two sample periods are shown in Table 1. A simple pretest of differences between variances is also presented in the table. With the exception of the residual error variance component in the later period of the natural gas equation, the variances were significantly different for all fuels. Electricity and petroleum exhibited a large increase in the error variance component, while all variance components in the petroleum equation increased in the latter time period.

Because of these differences in variance parameters between the two periods, it is necessary to transform each sample period's data using the estimated variance parameters from that period.[6/] In that way, the resulting transformed data has identical underlying error structures, in particular, an identity variance-covariance matrix. Failure to correct the subsamples separately will yield biased parameter estimates that may fail to separate changes in the parameters from changes in the variance-covariance matrix.

Estimates of the structural parameters and Chow tests for structural change are presented in Table 2 for the transformed data. The results indicate significant changes in the structural parameters over the 1971-82 period for petroleum and electricity, but could not reject the hypothesis of no structural change in the case of natural gas. This evidence of structural change for electricity is consistent with that reported in Sutherland (1983). Structural change in the residential sector's demand for distillate fuel was identified by Uri and Hassanein (1984). Neither of these studies explicitly considered the possible change in the variance-covariance matrix.

As shown in Table 2, petroleum and electricity consumption parameters changed significantly between the two periods. In both cases, the coefficient on the lagged dependent variable decreased, indicating that the speed of adjustment, λ, is larger. The increase in the speed of adjustment was especially great for petroleum. For purposes of comparison, it is possible to calculate the length of time required for half of the adjustment to an exogenous shock in one of the independent variables to be completed based on the value of λ. Based on the lagged consumption coefficients, half of the long-run adjustment in petroleum consumption would have taken 12.5 years based on 1971-74 estimates, in contrast to only 2.1 years given the 1979-82 estimates. Similarly for electricity, the time needed to achieve 50-percent of the adjustment to a shock dropped from 10.6 to 5.6 years.

Furthermore, the own-price and cross-price elasticities increased in absolute value in the petroleum and electricity equations between the two time periods. The changes in the petroleum equation were especially dramatic, registering the effect of the major price shock generated by OPEC's actions. The prices of natural gas and electricity were sheltered to a degree by regulation and, in the case of electricity, alternative sources of cheaper power. Petroleum consumption, therefore, has apparently changed so as to reflect the increased volatility in oil prices: movements in oil prices now generate rapid and relatively large changes in petroleum consumption.

The natural gas equation did not demonstrate increased sensitivity to energy price movements. Adjustments in natural gas consumption to exogenous shocks became only slightly more rapid, falling from 9.3 years to 8.8 years for 50-percent of the adjustment. Estimated own and cross-price elasticities decreased in the later period, although the coefficients were insignificant in both periods.

Electricity demand was found to respond positively to heating and cooling changes, while natural gas and petroleum demand responded positively to heating changes. Surprisingly, the coefficients on the weather variables increased in the later period, which would seem to be inconsistent with a theory of increasing energy efficiency and consciousness.

V. Conclusions

The results suggest that the previous energy price shocks have significantly changed the residential demand for energy, particularly the demand for petroleum and electricity. Generally, demand for energy is more elastic and the sensitivity to the price of substitutes has increased. The speed of adjustment to changes has also increased.

The structural changes in energy demand lead to questions regarding the validity of many past energy demand estimates. Data from before the mid-70's are not likely to provide meaningful estimates regarding current consumption behavior. Given the lag in adjusting the capital stock of energy consuming appliances, it is important to use observations that allow full adjustment to previous energy price shocks.

Because of the long lags needed to respond to price changes it does raise the question whether demand has undergone additional structural change. During the latter time period, 1979 to 1982, full adjustment to the increase in energy prices resulting from natural gas deregulation and the Iranian revolution probably has not occurred. No doubt the disparity between the early and late periods would be greater if more recent data was available. Further, the results suggest that the magnitude of recent downward price movements may induce further structural change. Direct use of these results for predicting current behavior is difficult because of the likely asymmetry in demand response.

TABLE 1:

Stability of the Variance-Covariance Structure

	Cross-Section Variance Component	Time-Series Variance Component	Residual Error Variance Component
Electricity			
71-74	.0004369	.0004920	.0004581
79-82	.0003460	.0001083	.0016943
F-statistic	1.26*	4.54*	3.70*
Natural Gas			
71-74	.0013872	.0011444	.0047871
79-82	.0067478	.0004456	.0047666
F-Statistic	4.86*	2.57*	1.004
Petroleum			
71-74	.0010140	.0010299	.0032341
79-82	.0268856	.0028296	.0219523
F-statistic	26.51*	2.75*	6.79*

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* Significant at .05 level.

TABLE 2
Estimation Results

Electricity

Year	intercept	lagged dependent variable	own price	natural gas price	heating	cooling
71-74	9.4396	0.9330	-0.2357	0.3961	0.0018	0.0006
	(5.19)	(59.79)	(-6.31)	(2.91)	(3.77)	(2.63)
79-82	3.6509	0.8845	-0.2950	0.4930	0.0063	0.0006
	(3.45)	(35.27)	(-5.72)	(3.13)	(3.59)	(2.84)

F-statistic for absence of structural change: 18.16

Natural Gas

Year	intercept	lagged dependent variable	own price	electricity price	heating
71-74	3.7701	0.9280	-1.1765	0.2270	0.0017
	(.83)	(41.13)	(-1.17)	(1.32)	(.98)
79-82	-1.5713	0.9246	-0.8159	0.2158	0.0097
	(-0.40)	(41.30)	(-0.96)	(1.78)	(3.69)

F-statistic for absence of structural change: 2.10

Petroleum

Year	intercept	lagged dependent variable	own price	natural gas price	heating
71-74	4.4601	0.9460	-1.2162	0.5281	0.0011
	(1.80)	(78.24)	(-4.20)	(1.08)	(1.11)
79-82	1.9776	0.7236	-1.7434	3.1007	0.0028
	(0.40)	(28.32)	(-2.83)	(3.87)	(1.06)

F-statistic for absence of structural change: 27.79

Note: t-statistics in parenthesis.

FOOTNOTES

1. See Houthakker, Verleger, and Sheehan (1974); Lakshmanan and Anderson (1980); Beierlein, Dunn and McConnon (1981); and Houthakker (1980).

2. Houthakker and Taylor suggest that the lagged value of income or the percentage change in income might be relevant explanatory variables.

3. There are several possible explanations for the lack of significance of income. First, the insignificance of the income variable may result from the use of average per capita income. Because the data set has cross-sections of per capita averages, the range is somewhat limited. Other studies that use household data on individual income and consumption may be able to identify the income effects. A second possible explanation may be that energy does form a significant portion of a household's expenditures. An increase in energy prices can effect energy consumption through a significant negative income effect in addition to the price effects. Another explanation is that energy is a complement to goods with a very low or even negative income elasticity of demand. For example, as income increases so does spending on vacations, eating out, and other outside of the home entertainment, all activities that reduce the consumption of energy by the residential sector. This does argue that the price of complements, such as out of the home recreation and appliances, should be included in the demand functions. Given the large number and uncertain ability to accurately price them we did not undertake this. Furthermore, Houthakker (1980) points out that the usefulness of including complements, such as appliances, has not been demonstrated and has led to theoretically implausible results.

4. Garbacz (1983) is only the most recent of many studies that have used average rather than marginal prices. The arguments for using average price are: 1) Average prices are readily available, but obtaining marginal prices for each of the cross sections in our study is an enormous task; 2) consumers may not distinguish and respond accordingly to the marginal price, rather they respond to their total bill [Dubin and McFadden (1980)]; 3) average prices have been found to yield comparable elasticities as those using marginal prices [Halvorsen (1975)].

5. In contrast to this paper and the others mentioned, Beierlein, Dunn, and McConnon (1981), estimated a series of equations using the seemingly unrelated approach. They selected this method because of the rather large covariance between the error terms of the different sectors. They also found that the covariance between the different fuels within sectors was relatively small indicating that any increased efficiency for joint estimation within a sector is small.

6. The individual subsamples were tranformed using the method described in Judge, Griffiths, Hill and Lee (1980), page 343.

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