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12 September 1977

Residential Natural Gas Consumption: Evidence That Conservation Efforts to Date Have Failed

Abstract. *A new short-term natural gas consumption model is developed, tested against American Gas Association sales data, and applied to the question of the effectiveness of conservation efforts. The results indicate that unit residential gas-heating sales per heating degree-day have remained constant in four major gas-consuming regions during the period 1974 to 1976 and that heating sales have not been affected by the recent sharp changes in price.*

The sum of the average heating degree-day values for a particular period times the number of heating customers in the area of interest has been used for many years by heating and gas service company engineers as an accurate index of fuel consumption for space heating. Hu (*1*) developed such a linear model for use by the American Gas Association (AGA) in estimating annual residential heating sales for each state. In the engineering estimates it is assumed that the heating degree-day elasticity (*E*) for space heating fuel consumption is unity (*2*).

On the other hand, nationwide studies of residential natural gas use based on econometric models indicate that *E* lies between 0.45 and 0.71. A recent analysis of 1970 data by use of a linear model gives *E* values of 0.71 for space-heating use and 0.40 for total residential use (*3*). A comprehensive study of the entire period 1970 to 1975 by use of a log-normal model gives *E* values of 0.45 for space-heating use and 0.345 for total residential use (*4*). Similarly, log-normal analyses of all residential fuel use in 1971 yield *E* values of 0.64 for space-heating use and 0.496 for total residential use (*5*).

Fuel use predictions based on the engineering and the econometric models can differ enormously, and such predictions are crucial to energy planning, conservation, and policy decisions (*5*). In view of the current need to manage our energy resources carefully, it is important that such major differences be resolved so that reliable information will be available for use at every management level.

In this report, we develop and test a simple linear model that appears to reconcile the results of the engineering and the econometric models, demonstrates that *E* values are currently close to 1.0 for space-heating use and 0.7 for total residential use, and provides indices that may be used to evaluate the effects of price change and conservation efforts on residential consumption of natural gas.

Testing the model. According to the simplest linear model, within a state *i* the quarterly residential natural gas sales are given by

$$s_i = jc_i + kh_iz_i \qquad (1)$$

in which c_i and h_i are the number of *total residential* and *residential heating* customers, respectively; z_i is the sum of population-weighted heating degree-days for the quarter; and *j* and *k* are parameters to be determined. We thought that a simple linear model could adequately describe and predict quarterly sales within a state because of our earlier experience with data for Missouri (*6*). In the course of developing a state model, we acquired daily gas sendout data for the heating season 1973 to 1974 directly from the utility firms serving Missouri. Whether the data are displayed weekly (*6*) or quarterly as in Fig. 1, the relationship between degree-days and sales values is linear.

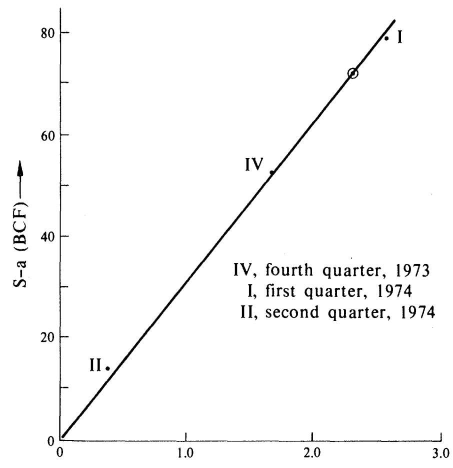

Fig. 1. Temperature dependence of natural gas sales in the state of Missouri, 1973–1974 heating season. The data are aggregated by quarter; *a* is fixed sales, 37.5 billion cubic feet (*BCF*) per quarter; *S* is total sales in all sectors. The following values were used: (1973-IV) *S*, 90.25; $S - a$, 52.75; $\bar{z}$, 1.67; (1974-I) *S*, 116.6; $S - a$, 79.1; $\bar{z}$, 2.50; (1974-II) *S*, 36.9 (8-week period only); $S - a$, 13.8; $\bar{z}$, 0.37; (⊙) $S - a$, 72.8; $\bar{z}$, 2.305. For the three quarters, the total $S - a = 145.6$; total $\bar{z} = 4.61$. (⊙) Sum of the sales ($S - a$) and sum of the degree-days plotted at half their values. The straight line defines the average ($S - a$) sales per degree-day. Departures from this line indicate seasonal differences from the annual norm.

The accuracy of prediction of the linear model can be tested by comparing reported sales with predicted sales calculated by using values of *j* and *k* derived from base period equations—that is, two simultaneous equations like Eq. 1 in which the subscripts *i* denote known customer sales—and degree-day data for the two quarters preceding the one under test.

Such testing would be possible if quarterly data for natural gas sales were available by state. Unfortunately, sales information is available in general only by census division (*7*). Therefore, to test the simple linear model, we modified it so that it predicts sales values for multistate census divisions. We chose a form that resembles Eq. 1 and is simply related to it

$$S = jC + kH\bar{z} \qquad (2)$$

in which *S* is the regional quarterly sales; *C* and *H* are, respectively, the number of *total residential* and *residential heating* customers in the region; and $\bar{z}$ is the regional weighted mean number of accumulated heating degree-days in the quarter, defined by

$$H\bar{z} \equiv \sum_i h_iz_i \qquad (3)$$

A second important modification of Eq. 1 was necessary. Experience in comparing predicted sales with sales reported by the AGA suggested that $\bar{z}$ is a function of a sales reporting lag. To use the AGA sales data as given, we defined a lag parameter, *x*, which shifts $\bar{z}$ so that it corresponds to the mean number of degree-days in the lagged reporting period. This leads to

$$H\bar{z}(x) \equiv x \sum_i h_i\Delta z_i + \sum_i h_iz_i' \qquad (4)$$

or

$$H\bar{z}(x) \equiv Ax + B \qquad (5)$$

where *A* and *B* represent the summed quantities, z_i' is the number of heating degree-days in the 3-month period lagging the calendar quarter by 1 month,

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and $\Delta z_i = z_i - z_i'$. Thus $H\bar{z}(1) = A + B = \Sigma_i h_i z_i$ as in Eq. 3 and $H\bar{z}(0) = B = \Sigma_i h_i z_i'$.

To obtain base period values for the three unknowns, j, k, and x, we had to use sales, degree-day, and customer data from three recent past quarters; that is, we needed three independent equations of the form

$$S = jC + kH\bar{z}(x) \quad (6)$$

Since k and x are determined most precisely by use of quarters containing reasonably large numbers of degree-days, we did not include third (summer) quarters among the three in the base periods. Thus, each succeeding base period contains the preceding first, second, and fourth quarters. We treated third-quarter sales estimates uniquely, separate from the linear model developed here.

Explicit form of the base period equations. Substituting Eq. 5 into Eq. 2 for three successive quarters gives three independent linear (*8*) equations in the three unknowns j, kx, and k

$$S_1 = jC_1 + kxA_1 + kB_1 \quad (7)$$

$$S_2 = jC_2 + kxA_2 + kB_2 \quad (8)$$

$$S_3 = jC_3 + kxA_3 + kB_3 \quad (9)$$

A 3 × 3 matrix inversion and multiplication operation simultaneously solves Eqs. 7 to 9 for j, kx, and k. We predicted sales in the following quarter, S_4, by use of appropriate values of C_4, A_4, and B_4 derived from actual or predicted customer and degree-day data and the j, kx, and k values derived from base period equations describing sales in the previous three quarters.

Test results. We compared the predicted sales values, denoted by LM (for linear model) in Table 1, with those actually reported by the AGA (*7*). Data for the winter, spring, and fall quarters of 1975 and 1976 and the winter quarter of 1977 for the Middle Atlantic, East North Central, West North Central, and West South Central census divisions are presented in Table 1.

Values for some quarters (marked by asterisks in Table 1) were excluded from the test of the accuracy of the model because the reported sales values were skewed due to a large shift in lag period. This may be seen by inspection of the x values. When such a quarter was included in the successive three-quarter period for the calculation of new j, k, and x values, a dramatic change in x resulted. This indicates that the reporting period lag for that quarter differed appreciably from the mean lag of the previous three quarters making up the base period. Any large change in reporting period causes the period for which sales are reported to differ from that for which sales are predicted and leads to spurious differences between predicted and reported sales data. The effect is particularly strong in the second and fourth quarters. To avoid this problem in testing the model, we used only data for which the lag value in the period for which sales are predicted is within 10 percent of the lag value in the base period.

A comparison of the predicted with the actual sales values for the 17 included quarters in Table 1 shows a net difference of 20.5 out of a total of 4508.9 trillion Btu's, an agreement to 0.5 percent. The sum of the 17 absolute differences is 55.9 trillion Btu's, for an agreement of 1.2 percent. We conclude that the linear model is an accurate predictive tool when the reporting period lag and the j and k values remain reasonably

Table 1. Comparison of predicted and reported sales data.

Year	Quarter	Sales (trillion Btu's)		Δx*	Δ sales (trillion Btu's)	
		AGA	LM		AGA	LM
			Middle Atlantic division			
1975	I	341.0	340.3	0.427-0.425	−5.2	−5.9
	II†	168.9	180.4	0.425-0.483		
	IV†	197.5	183.0	0.483-0.571		
1976	I	353.1	353.0	0.571-0.571	12.1	12.0
	II	145.7	150.7	0.571-0.595	−23.2	−18.2
	IV	265.8	266.7	0.595-0.589	68.3	69.2
			East North Central division			
1975	I	676.7	684.3	0.041-0.039	−18.8	−11.2
	II†	390.8	430.4	0.039-0.176		
	IV†	342.0	333.0	0.176-0.201		
1976	I	670.1	688.7	0.201-0.191	−6.6	12.0
	II†	322.3	347.1	0.191-0.281		
	IV	465.4	463.4	0.281-0.287	123.4	121.4
			West North Central division			
1975	I	260.6	255.1	0.327-0.316	14.4	8.9
	II†	107.2	115.5	0.316-0.376		
	IV	126.4	123.5	0.376-0.397	−3.3	−6.2
1976	I	240.2	238.8	0.397-0.396	−20.4	−21.8
	II	94.2	91.1	0.396-0.375	−13.0	−16.1
	IV	166.7	167.5	0.375-0.368	40.3	41.1
			West South Central division			
1975	I	192.3	189.7	0.226-0.216	6.0	3.4
	II	88.8	90.5	0.216-0.236	13.4	15.1
	IV	102.1	100.2	0.236-0.260	−3.4	−5.3
1976	I	179.6	183.5	0.260-0.266	−12.7	−8.8
	II†	77.4	83.6	0.266-0.335		
	IV	140.2	142.4	0.335-0.309	38.1	40.3

*Each entry consists of two values; the first is x for the base period, the second is x for the period calculated after the fact that includes the new quarter. †Values for this quarter were excluded from the test of the model, as explained in the text.

Table 2. Linear model parameters.

Year and quarters	Middle Atlantic division			East North Central division			West North Central division			West South Central division		
	j	k	x	j	k	x	j	k	x	j	k	x
74-I, II, IV	6.63	25.2	0.427	14.8	20.1	0.041	6.97	20.5	0.327	12.2	20.6	0.226
II, IV, 75-I	6.54	25.3	0.425	15.4	19.7	0.039	5.98	21.3	0.316	12.1	21.1	0.216
IV, 75-I, II	5.02	26.4	0.483	11.4	21.3	0.176	3.82	22.0	0.376	11.7	21.4	0.236
75-I, II, IV	6.78	25.2	0.571	12.2	20.9	0.201	4.54	21.8	0.397	11.9	21.3	0.260
II, IV, 76-I	6.78	25.3	0.571	13.8	19.6	0.191	4.20	22.0	0.396	12.2	20.4	0.266
IV, 76-I, II	6.11	25.7	0.595	11.0	20.8	0.281	5.17	21.6	0.375	10.9	21.8	0.335
76-I, II, IV	6.03	25.8	0.589	11.1	20.8	0.287	5.04	21.7	0.368	10.8	21.8	0.309

constant. The latter are not expected to change dramatically between a base period and the following quarter because they depend on ingrained habits of residential gas usage. Short of a real emergency, such habits are slow to change.

A second test was used to examine the question of the E value. The difference between the sales in a particular quarter and the reported sales in the same quarter 1 year earlier is shown in Table 1 for the reported and predicted sales (Δ sales). Excluding the results for the East North Central division in the first quarter of 1976, all the predicted and actual differences in sales are in the same sense. The ratio of the sum of the absolute values of the actual differences to that of the predicted differences in the remaining 16 quarters is 416.0/404.9 or 1.03. Since the predicted value differences were based on an assumed E value of 1.0 and the differences for the predicted and actual values closely agree, the test supports the assumption of $E = 1.0$.

Table 3. Price elasticity of space-heating and non-space-heating residential use.

Division	Price ($/million Btu's)*			1974 to 1976			E_j	E_k
	1974	1975	1976	dP/P	dj/j	dk/k		
Middle Atlantic	2.02	2.26	2.46	0.22	−0.09	0.024	−0.41	0.11
East North Central	1.43	1.56	1.77	0.24	−0.25	0.035	−1.04	0.15
West North Central	1.30	1.37	1.45	0.12	−0.28	0.059	−2.3	0.49
West South Central	1.21	1.34	1.63	0.35	−0.12	0.058	−0.33	0.17

*Obtained from (7) by dividing residential sales into residential revenues, then normalizing by the annual *Consumer Price Index*.

Table 4. Price and degree-day elasticities of quarterly residential sales by division.

Division	Quarterly variable means (standard deviations)			P ratio*	Elasticity at variable means	
	S/C (10^6 Btu per customer)	$\bar{z}$ (degree-days)	P (\$/ 10^6 Btu)		$E_{\bar{z}}$	E_P
East North Central	41.9 (21.2)	1570 (1190)	1.54 (0.11)	1.24	0.66	−0.19
Middle Atlantic	26.3 (13.8)	1430 (1070)	2.24 (0.22)	1.29	0.73	0.13
West North Central	37.9 (22.8)	1560 (1240)	1.36 (0.07)	1.17	0.76	0
West South Central	22.9 (11.7)	570 (550)	1.40 (0.18)	1.40	0.51	−0.09

*Fourth-quarter 1976 price divided by first-quarter 1974 price.

Inferences from the model parameters. To the extent that the tests described above have validated the linear model, the values and changes in value of the model parameters are meaningful. The linear model parameters listed in Table 2 are in each case the triplet of j, k, and x values that uniquely solve Eqs. 7 to 9 for the reported sales in sets of successive quarters. These triplet values and the following conclusions drawn from them are quite sensitive to the reported sales values. We assume here that the sales values reported by AGA are correct.

We conclude from the sets of x values that the utility companies reporting from the Middle Atlantic division have in the aggregate the least reporting lag, currently about 2 weeks, and those from the East North Central division have the greatest lag, currently about 3½ weeks. All divisions have made some progress in reducing the reporting lag since the beginning of 1975.

The j values exhibit a significant drop in all divisions. The decline is particularly noticeable when the last two quarters of 1976 are included. We conclude that conservation-inducing factors have had an effect in recent quarters on the nonheating uses of residential natural gas. There is a large difference in j values between the divisions, indicating great differences in the saturation and use of nonheating appliances.

The k values lead to three interesting observations. First, these values have remained unchanged or have risen slightly during the past 3 years. Since k represents the space-heating gas use per degree-day per heating customer, this leads us to conclude that efforts during 1974 to 1976 to reduce the heating use of natural gas have failed. This is a particularly important conclusion, since about half of the nation's residential space-heating use of natural gas occurs in these four divisions. Second, k does not vary between the East North Central, West North Central, and West South Central divisions. This tends to refute the widely held idea that because of better insulation and construction, residences in the northern states use less space-heating fuel per unit coldness than those in the South.

Finally, residential heating customers in the Middle Atlantic division are currently using about 20 percent more natural gas per unit coldness than those in the other divisions. We have no information that could help explain this, although some obvious possible explanations include widespread use of low-efficiency furnaces, overheating, effects of climate differences between the divisions (such as amount of winter sunlight, wind, and humidity), and less than optimum usage of insulation. The amount of gas that could be saved by identifying and eventually correcting the causes of this apparent overuse of fuel is substantial: in recent years the heating use of natural gas in the Middle Atlantic division has averaged about 600 trillion Btu's. If the use per customer could be brought down to the average in neighboring divisions, only about 500 trillion Btu's per year would be needed.

We calculated the fraction of residential natural gas devoted to heating by adding the $k(Ax + B)$ values for the 12 quarters in 1974 to 1976 (including the third quarters) and dividing the sum by the total reported residential sales values. This gave the result 0.69 for the East North Central division, a region with substantially higher than average per capita use of nonheating appliances. We estimate that nationwide, the current fraction of residential natural gas devoted to heating is well above 0.70. This is consistent with Seidel's results (*4*) but is higher than values obtained with other econometric models (*3, 5*) and the current AGA estimate of 0.65.

Price influences. In the linear model, the effects of fuel price changes and other factors that promote conservation will appear indirectly as changes in j and k. In view of the sharp rise in the real price of residential natural gas between 1974 and 1976 (Table 3), we had expected to find a downward trend in the j and k values. Table 3 shows the results of a study of the relationship between real price changes in this period to unit changes in heating and nonheating use. The E_j values show the expected negative influence of price rise on nonheating use, but the variability indicates that more data are required if an elasticity relationship is to be used in predicting the impact of future price rises on nonheating use. On the other hand, the E_k factors show a small positive influence of price rise on space-heating use. The insensitivity of heating use to price rise suggests that because of the lack of other fuels at competitive prices and the relative affluence of the average gas-heating customer, the customers have absorbed the higher costs without appreciably changing their heating habits.

We obtained the heating degree-day elasticity for total residential sales by use of a double-log regression of degree-days (*9*) and natural gas price (*10*) on sales per residential customer in the East North Central division for the nine heating-season quarters from 1974 through 1976. The resulting equation is ln (sales per customer) = 3.532 − 0.214 ln(price) + 0.706 ln(degree-days). The R^2 (correlation value coefficient) is 0.99. Thus we find heating degree-day and price E values of 0.71 and −0.21, respectively, for total per capita residential use. As noted above, the negative effect of price rise is solely on the nonheating portion of the residential use.

Following a standard linear regression approach, we reached essentially similar conclusions with respect to all four divisions. We used degree-day values ($\bar{z}$) as one variable and the average quarterly price per 10^6 Btu's (P) paid by residential customers as the other variable to explain the variation in quarterly consumption per customer (S/C)

$$S/C = a_0 + a_1\bar{z} + a_2P \quad (10)$$

where $\bar{z}$ is obtained from Eq. 5 and the x values in Table 2, and P is obtained as the indexed ratio of quarterly revenues (R) to quarterly sales (S) as reported by AGA. A quarterly index I_q permits the price to be expressed in terms of 1975 dollars (*11*) as

$$P = \frac{R}{S} I_q \quad (11)$$

To estimate the coefficients, we rewrote Eq. 10 in stochastic form, adding the discrete variable Q_3 in order to handle third-quarter consumption shifts in the Middle Atlantic and West South Central divisions: $Q_3 = 1$ for third-quarter data and zero otherwise

$$S/C = a_0 + a_1\bar{z} + a_2P + e_1 + a_3Q_3 \quad (12)$$

Results for the 12 quarters in 1974 to 1976 are presented in Table 4. All coefficients were significant to at least the 5 percent confidence level, and all R^2 values were 0.999, indicating that the variables completely explain the quarterly variation in gas consumption.

Thus, when seasonal usage trends are accurately incorporated by use of lag-corrected temperature data and quarterly sales data, the econometric model results are shifted and become consistent with those derived from the engineering models.

Other implications. The current and historical sales data compiled by the AGA are widely used by energy professionals. For many purposes other than demand forecast modeling, it is unimportant if the data lag the nominal calendar quarter by 2 to 4 weeks, but for conservation models, as indicated in this report, the lag can be very important. For those who need to correct the AGA data for lag, Eq. 6 provides a simple means of doing so. For each quarter, one makes use of the known C, A, and B values and the appropriate j and k values, but substitutes 1.0 for the x value in the equation. The resulting expression gives the sales for the true calendar quarter.

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7. The *Quarterly Report of Gas Industry Operations* (Bureau of Statistics, American Gas Association, Arlington, Va.) includes natural gas sales, customer, and revenue information for each of the nine U.S. census divisions; the annual *Househeating Survey* (American Gas Association, Arlington, Va.) contains househeating customer data.
8. It can be shown that x is a unique function of S, C, A, and B; the apparent quadratic form kx is thus misleading.
9. Calculated to match the exact lagged sales-reporting periods.
10. Normalized to 1975 dollars by use of the *Consumer Price Index* (Bureau of Labor Statistics, Department of Labor, Washington, D.C.) Smoothed to give a uniform rise each quarter.
11. The quarterly index $I_q = GI_qCI_{75}/GI_yCI_q$, where GI_q is the price index for natural gas in quarter q in year y, GI_y is the average price index for gas in year y, CI_{75} is the average consumer price index for the region in 1975, and CI_q is the consumer price index for the region in quarter q. The source of index data is *Monthly Labor Review* (Bureau of Labor Statistics, Department of Labor, Washington, D.C.).

3 October 1977

Localized Compressional Velocity Decrease Precursory to the Kalapana, Hawaii, Earthquake

Abstract. *A delay in the arrival times of compressional or* P *waves of 0.15 to 0.2 second from deep distant earthquakes has been detected at the closest seismograph station to the 20 November 1975 earthquake at Kalapana, Hawaii (surface-wave magnitude* $M_s = 7.2$*). This delay appeared approximately 3.5 years prior to the quake, and travel times returned to normal several months before it. The* P*-wave arrival times at other nearby stations remained constant during this period, an indication that the decreased velocity implied by the delay in travel time was associated with this normal-faulting earthquake and was confined to distances less than 20 kilometers from the epicenter.*

Since the original Russian reports (*1*) of seismic velocity decreases prior to earthquakes, workers in the United States, Japan, and other countries have searched for similar effects before other earthquakes in hopes of using this phenomenon as a predictive tool. A few successes have been reported (*2*) but only for small (surface-wave magnitude $M_s < 7$) thrust earthquakes (*3*), and negative findings are common (*4*). Therefore, the detection of decreased P-velocities preceding the normal-faulting earthquake ($M_s = 7.2$) near Kalapana, Hawaii, is of considerable interest for earthquake prediction research.

The data used to identify the velocity decrease were relative P-residuals from deep (> 500 km) Fiji-Tonga earthquakes (*5*) (see inset, Fig. 3). A residual is the difference between the observed and the computed arrival times of a seismic signal. One obtains a relative residual by subtracting from this value the residual of a nearby reference station. For a given earthquake, this process results in the near cancellation of contributions arising from ray path variability at the source, in the lower mantle, and in the upper mantle beneath the receiver. Near-receiver crustal variations, caused by any anomalous temporal behavior of inter-