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Energy Demand and Fuel Choices in the Pulp and Paper Industry

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OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

This report presents a generalized market share model in which the restrictive constraints on cross-price coefficients need not be imposed yet in which all demand elasticities are uniquely determined. The model is applied to estimating aggregate energy demand and fuel choices for the pulp and paper industry. The structural equations are estimated by a generalized least squares procedure using state-level census data for 1971 and 1974. The econometric results support the argument that price coefficients should not be constrained. Furthermore, the "third-price" coefficients are statistically significant in the fuel-split equations.

The empirical results show that the aggregate demand for purchased boiler fuels in the paper industry is responsive to changes in energy prices. Also, the market shares of boiler fuels are highly dependent upon their prices; the own-price elasticities are all considerably greater than unity. These results, along with several large cross-price elasticities, suggest that the possibility of interfuel substitution is rather strong in the paper industry. The market share elasticities estimated in this study are used in the economic/engineering simulation model of energy use in the paper industry being developed at the Oak Ridge National Laboratory for the Department of Energy.

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ENERGY DEMAND AND FUEL CHOICES IN THE PULP AND PAPER INDUSTRY

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1. INTRODUCTION

The purpose of this study is to develop a fuel choice model for the pulp and paper industry [this industry is identified by the standard industrial classification (SIC) code as SIC-26]. The estimated fuel-share elasticities are used in the economic/engineering simulation model of energy use for the paper industry being developed at Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE).

This study generalizes the fuel-choice model developed by Baughman and Joskow.¹ In the generalized model described here, it is shown that the rigid constraint that all cross-price coefficients be identical does not have to be imposed, as it was by Baughman and Joskow, to determine uniquely all demand elasticities. Furthermore, various demand and fuel-share elasticities are analytically derivable and estimable. This feature of the model facilitates the understanding of important factors that may affect energy demand in the paper industry in response to changes in energy prices.

2. ENERGY USE PATTERN IN THE PAPER INDUSTRY

The paper industry ranks fourth in terms of energy consumption among manufacturing industries in the United States (following chemicals, petroleum refinery, and primary metal production), and it is the leading manufacturing consumer of fuel oils. According to the U.S. Bureau of the Census, the pulp and paper industry (SIC-26) consists of six SIC

subindustry groups. As shown in Table 1, paper mills (SIC-262) and paperboard mills (SIC-263) are the major energy-consuming segments of the paper industry. Together they accounted for 81% of total purchased energy in 1974 even though their shares of value added accounted for only 39% of the industry's total. These two industry groups also have a high energy intensity in terms of energy use per dollar of value added (Table 1). Note, however, that pulp mills integrated with paper mills, paperboard mills, or other paper product mills were not included in SIC-261. Thus, the pulping segment was larger than that shown under SIC-261. In fact, Kaplan² estimated that the energy requirement for the entire industry is split fairly evenly between processes related to pulp making, chemical recovery, and bleaching on one hand and pulp drying and paper and paperboard making on the other.

Table 1. Value added, purchased energy, and energy intensity of subindustry groups in the pulp and paper industry (SIC-26) for 1974

SIC code	Group	Value added (10 ⁶)	Total purchased energy sources (10 ¹² Btu)	Energy intensity ^a (10 ⁶ Btu/\$)
261	Pulp mills	779.3	85.7	0.110
262	Paper mills (except building papers)	4,346.9	572.7	0.132
263	Paperboard mills	2,980.0	510.9	0.171
264	Miscellaneous converted paper products	5,781.2	65.5	0.011
265	Paperboard containers and boxes	4,800.2	53.2	0.011
266	Building paper and board mills	269.6	42.7	0.158
Total	(SIC-26)	18,957.2	1330.7	0.070

^aEnergy intensity equals the total purchased energy sources divided by the value added.

Source: U.S. Bureau of the Census, *Annual Survey of Manufacturers*, U.S. Government Printing Office, Washington, D.C., 1974.

Table 2 and Fig. 1 show the historical distribution of purchased energy by fuel type in the paper industry. In 1947 coal accounted for 70% of the total amount of energy purchased by the industry, although its share declined dramatically to only 16% in 1975. This declining trend was due to the availability of cleaner fuels such as natural gas and fuel oils in the 1950s and 1960s and more stringent pollution control standards imposed in the late 1960s. But the decline in the share of coal is thought to be lessening and may actually be reversing. The natural gas share increased steadily until early 1970 when the gas shortage occurred. The availability of fuel oil resulted in an increase in its use through the 1973 energy crisis, and since 1974 it has become

Table 2. Distribution of purchased energy among fuels

Year	Total purchased energy (10 ¹² Btu)	Individual fuel shares (percentages of total purchased energy)				
		<u>Coal</u>	<u>Natural gas</u>	<u>Fuel oil</u>	<u>Electricity</u>	<u>Others</u>
1947	556.9	70	13	13	4	0
1954	645.6	51	19	20	6	4
1958	798.3	48	28	19	5	0
1962	922.1	43	30	20	6	1
1967	1050.1	32	35	23	8	2
1971	1315.7	19	38	29	9	5
1972	1287.9	18	35	39	7	2
1974	1330.7	17	33	34	11	5
1975	1083.1	16	32	42	8	2

Sources: U.S. Bureau of the Census, *Census of Manufacturers and Annual Survey of Manufacturers*, U.S. Government Printing Office, Washington, D.C., selected years, 1947-71, 1940. American Paper Institute, Inc., Fuel and Energy Division, New York, ;972. 1975.

Fig. 1. Shares of purchased fuels used by the paper industry, 1947-75.

the energy resource most used by the industry. The share of purchased electricity has been small relative to other major fuels, even though it increased significantly throughout the 1947-70 period. It must be noted that the industry has been generating its own electricity using back-pressure or extraction steam turbines driven with high-pressure steam at modern electric-station conditions. In 1972 nearly 50% of the electrical requirements was supplied by in-plant power generation. Some individual plants generate up to 100% of their electrical requirements.

In the paper industry, natural gas, coal, and fuel oils are used for generating process steam through boilers whereas electricity is used primarily for operating machine drives and pumps. Thus, a direct substitution between boiler fuels and electricity is usually not feasible (there is almost no electric boiler use by the industry). Because the

present study focuses on interfuel substitution of boiler fuels, electricity is excluded in the econometric analysis.

Other nonpurchased energy sources in the forms of spent liquor, bark, and logged wood also provide significant amounts of energy used for generating process steam. Duke and Fudali³ estimated that these waste fuels accounted for 43% of total energy consumption in 1975. Unfortunately, however, data on waste fuels are not adequate for econometric analysis. In this study, then, we deal with only the three major boiler fuels: natural gas, fuel oil, and coal.

3. A GENERALIZATION OF THE BAUGHMAN AND JOSKOW MODEL

In recent years there have been a number of models developed to estimate fuel choices and market shares of fuels. Major contributors include Anderson,⁴ Baughman and Joskow,¹ Chern,⁵ Lin et al.,⁶ Wilson,⁷ and the Federal Energy Administration (FEA).⁸ In this section, we review critically the shares model used by Baughman and Joskow and develop a generalization of their model. The Baughman and Joskow model is similar to the ones used by Anderson⁴ and the FEA.⁸ The reasons for choosing the Baughman and Joskow model are (1) it can be easily generalized and (2) the generalized model does not have the shortcomings encountered in the models used by Chern⁵ and Lin et al.⁶ Specifically, in the Chern model market shares are not bounded to be positive, whereas, in the Lin model an ad hoc constraint needs to be imposed in estimation. The Baughman and Joskow model implies that the ratio of consumption shares between any two forms of energy depends only on prices of those two energy forms - that is, not on prices of other energy forms - according

to the multinomial logit specification. Specifically, their model (disregarding for the moment nonprice factors and short-run adjustments) is

$$\ln\left(\frac{S_i}{S_j}\right) = \alpha_{ij} + \beta_{ij} \ln\left(\frac{P_i}{P_j}\right),$$

where S_i is the share of energy consumption for energy form i and P_i is the price of energy in form i . In this context, they focus on the two relationships

$$S_1 = A_{13} \left(\frac{P_1}{P_3}\right)^{\beta_{13}} S_3, \quad A_{13} = \exp(\alpha_{13}), \quad (1a)$$

$$S_2 = A_{23} \left(\frac{P_2}{P_3}\right)^{\beta_{23}} S_3, \quad A_{23} = \exp(\alpha_{23}), \quad (1b)$$

and the identity $S_1 + S_2 + S_3 = 1$ (where three forms of energy exhaust the set of possible alternatives) to explain the disaggregation of total energy consumption.

To consider the implications and restrictions imposed by Baughman and Joskow's model, note that substitution of Eqs. (1a) and (1b) into the identity implies that

$$S_1 + S_2 + S_3 = S_3 \left[1 + A_{13} \left(\frac{P_1}{P_3}\right)^{\beta_{13}} + A_{23} \left(\frac{P_2}{P_3}\right)^{\beta_{23}} \right] = 1,$$

or that

$$S_3 = \left[1 + A_{13} \left(\frac{P_1}{P_3}\right)^{\beta_{13}} + A_{23} \left(\frac{P_2}{P_3}\right)^{\beta_{23}} \right]^{-1}. \quad (2)$$

However, substituting Eq. (2) into Eq. (1a) yields

$$S_1 = A_{13} \left(\frac{P_1}{P_3} \right)^{\beta_{13}} \left[1 + A_{13} \left(\frac{P_1}{P_3} \right)^{\beta_{13}} + A_{23} \left(\frac{P_2}{P_3} \right)^{\beta_{23}} \right]^{-1} \quad (3)$$

$$= \left[1 + A_{31} \left(\frac{P_3}{P_1} \right)^{\beta_{31}} + A_{21} P_1^{-\beta_{13}} P_2^{\beta_{23}} P_3^{\beta_{13} - \beta_{23}} \right]^{-1},$$

where

$$A_{31} = A_{13}^{-1},$$

$$A_{21} = A_{23}/A_{13}.$$

Their model is developed to treat all fuels symmetrically, however, S_3 depends only on the ratios of other prices to P_3 , whereas S_1 depends on the ratio of P_1 to P_3 and on another complex term involving all three prices. Symmetry is achieved only by imposing the constraint $\beta_{13} = \beta_{23}$, in which case the latter term involves only the ratio of P_2 to P_1 . Baughman and Joskow, in fact, impose this constraint under the claim of maintaining long-run consistency.*

The need to impose such arbitrary constraints, however, suggests that some important assumptions may thereby be attached to cross-price elasticities by attempting to explain the ratio of shares without using prices of other energy forms. Hausman,⁹ in his review of the FEA model, pointed out that such an econometric specification imposes very strong

* While Baughman and Joskow never clearly define their concept of long-run consistency, it apparently refers to the property of obtaining the same results over a long period of time regardless of which two of the three share equations are used in the analysis.

assumptions on the structure of underlying demands. Clearly, if consumption of each energy form depends only on its own price, then the ratio of shares (the ratio of consumptions of the two forms) depends only on the two prices. But in such a case all cross-price elasticities are zero. Neoclassical demand theory, however, would have each consumption quantity possibly depending on all prices, and, even with partial separability, one could not expect to untangle the interrelationships between various fuel forms.

Intuition indeed suggests that other fixed attributes associated with various fuel forms may cause a third price to be important in explaining the ratio of two forms. For example, the cleanliness associated with use of electricity, gas, and coal is much different. The same is true for ease of distribution. Thus, if gas is priced out of the market, the relative share of electricity compared to coal may be greatly enhanced in residential use because of aversion to coal use by many consumers. On the other hand, the need for economy may cause more of a shift from gas to coal in industry in the same situation; hence, the electricity-to-coal ratio would be impacted in the reverse direction in industry purely because of a "third-price" effect.

Given the importance of including alternative energy prices in explaining share ratios, it remains to be shown that a more general specification exists that is easily used and yet maintains symmetry (or the Baughman-Joskow concept of consistency). We focus on the static version of the generalized model because it is to be estimated empirically in this study. A dynamic formulation is presented in the Appendix.

The general model consists of the following two relationships for the case of three fuels:

$$S_1 = \alpha_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} S_3, \quad (4a)$$

$$S_2 = \alpha_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} S_3, \quad (4b)$$

along with the identity $S_1 + S_2 + S_3 = 1$. Here X represents other nonprice variables, α_{ij} is the scale parameter and γ_{ij} is the slope parameter of X in the equation relating the share of fuel i to the share of fuel j , and β_{ijk} is the slope parameter of the price of fuel k in the equation relating the share of fuel i to the share of fuel j . Note that the model in Eqs. (4a) and (4b) is the same as that expressed in Eqs. (1a) and (1b) except that all prices are included and cross-price elasticities are not restrained. Note also that Eqs. (4a) and (4b) completely specify all relative shares for the case of three fuels through application of the identity.

Substituting Eqs. (4a) and (4b) into the identity and solving for S_3 thus yields

$$S_3 = \left[1 + \alpha_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} + \alpha_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} \right]^{-1}. \quad (5)$$

Substituting Eq. (5) into Eq. (4a), for example, obtains

$$S_1 = \left[1 + \alpha_{13}^{-1} P_1^{-\beta_{131}} P_2^{-\beta_{132}} P_3^{-\beta_{133}} X^{-\gamma_{13}} + (\alpha_{23}/\alpha_{13}) P_1^{\beta_{231}-\beta_{131}} P_2^{\beta_{232}-\beta_{132}} P_3^{\beta_{233}-\beta_{133}} X^{\gamma_{23}-\gamma_{13}} \right]^{-1} \quad (6)$$

$$= \left[1 + \alpha_{31} P_1^{\beta_{331}} P_2^{\beta_{332}} P_3^{\beta_{333}} X^{\gamma_{33}} + \alpha_{21} P_1^{\beta_{211}} P_2^{\beta_{212}} P_3^{\beta_{213}} X^{\gamma_{21}} \right]^{-1},$$

where

$$\left. \begin{aligned} \alpha_{31} &= \alpha_{13}^{-1}, \\ \beta_{31p} &= -\beta_{13p}, \quad p = 1, 2, 3, \\ \gamma_{31} &= -\gamma_{13}, \\ \alpha_{21} &= \alpha_{23}/\alpha_{13}, \\ \beta_{21p} &= \beta_{23p} - \beta_{13p}, \quad p = 1, 2, 3, \\ \gamma_{21} &= \gamma_{23} - \gamma_{13}. \end{aligned} \right\} \quad (7)$$

It is thus clear that symmetry is attained without imposing additional constraints on the parameters already defined; this was not the case in comparing Eqs. (2) and (3). Immediate further observations also reveal that similar conclusions hold if Eq. (5) is substituted into Eq. (4). Thus, the desirable properties of the Baughman and Joskow model are attained in this general model without imposing their constraints on cross elasticities.

Estimation of the generalized model of this paper is also considerably easier because constraints across equations are not needed. One needs simply to estimate the logarithmic transformations of Eqs. (4a) and (4b). Ordinary least-squares (OLS) estimation of Eqs. (4a) and (4b) attains efficiency regardless of stochastic correlation among equations if all variables appear in every equation. Furthermore, from estimates

of Eqs. (4a) and (4b), one immediately obtains efficient estimates for all other possible equations, for example, $\ln(S_1/S_2)$, $\ln(S_3/S_1)$, $\ln(S_3/S_2)$, and $\ln(S_2/S_1)$.

A final consideration is the ease with which elasticities can be calculated. By using Baughman and Joskow's model, share elasticities with respect to prices can readily be determined from coefficient estimates. The same is also true, though, for the more general model proposed here. Specifically, one finds from Eq. (5) that

$$\begin{aligned} \frac{\partial S_3}{\partial P_j} &= -S_3^2 \left[\frac{\beta_{13j}}{P_j} \alpha_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} \right. \\ &\quad \left. + \frac{\beta_{23j}}{P_j} \alpha_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} \right] \\ &= -\frac{S_3^2}{P_j} \left[\beta_{13j} \frac{S_1}{S_3} + \beta_{23j} \frac{S_2}{S_3} \right] \\ &= -\frac{S_3}{P_j} \left[\beta_{13j} S_1 + \beta_{23j} S_2 \right] . \end{aligned}$$

Hence, the elasticity of S_3 with respect to price P_j is

$$E_{3j} = -\beta_{13j} S_1 - \beta_{23j} S_2 . \quad (8a)$$

Similarly, relationships in (7) imply that other elasticity estimates are easily obtainable from estimates of (4a) and (4b),

$$\begin{aligned} E_{2j} &= -\beta_{12j} S_1 - \beta_{32j} S_3 \\ &= (\beta_{23j} - \beta_{13j}) S_1 + \beta_{23j} S_3 , \end{aligned} \quad (8b)$$

$$\begin{aligned}
 E_{1j} &= -\beta_{31j} S_3 - \beta_{21j} S_2 \\
 &= \beta_{13j} S_3 + (\beta_{13j} - \beta_{23j}) S_2 .
 \end{aligned}
 \tag{8c}$$

In summary, it appears that the general model developed here adds needed flexibility to the approach used by Baughman and Joskow without adding further complications. A logical conclusion is thus, that the constraints used by Baughman and Joskow are not necessary to attain the symmetry and "consistency" properties they seek. Hence, their constraints should only be imposed on economic grounds (which they fail to provide).

4. THE ECONOMETRIC MODEL

To study only the behavior of fuel choices, one can estimate the set of fuel-share equations specified in Section 3. The studies of Anderson, Lin et al., and Wilson were conducted under this objective. In the study discussed here, however, both fuel choices and aggregate energy demand estimation are of interest. Thus, as done previously by Baughman and Joskow and by Chern, the model is extended to deal with the determination of energy demand in the paper industry. The complete model consists of two parts. The first determines aggregate demand for energy in all forms, and the second estimates market shares for three boiler fuels (natural gas, fuel oil, and coal).

The econometric variables are defined as follows:

Q_1 = quantity of fuel oils (distillate plus residual) demanded by the paper industry (10^6 Btu).

Q_2 = quantity of natural gas demanded by the paper industry (10^6 Btu).

Q_3 = quantity of coal demanded by the paper industry (10^6 Btu).

$Q = Q_1 + Q_2 + Q_3$ = total quantity of energy demanded (10^6 Btu).

P_1 = price of fuel oil used in the paper industry ($\$/10^6$ Btu).

P_2 = price of natural gas used in the paper industry ($\$/10^6$ Btu).

P_3 = price of coal used in the paper industry ($\$/10^6$ Btu).

V = value added in the paper industry ($\$10^6$).

W = wage rates of production workers in the paper industry ($\$/hr$).

M = costs of materials per dollar of value added in the paper industry (dollars/dollar).

Note that all quantity variables were adjusted by the appropriate efficiency factors. The efficiency factors for converting gross heating value of fuel to final heating value of steam are 0.81 (or 81%) for fuel oil, 0.76 for coal, and 0.78 for natural gas.¹⁰ The reported quantity for each fuel was multiplied by its efficiency factor to obtain the quantity figure in effective Btu's for end-uses. Similarly, the reported fuel prices were divided by their respective efficiency factors to obtain the comparable prices in dollars per effective million Btu.

Aggregate energy demand is assumed to be a function of the weighted average energy price, wage rates, costs of materials, and value added. The regression equation is expressed in logarithmic form as follows:

$$\ln Q = \lambda_0 + \lambda_1 \ln P + \lambda_2 \ln W + \lambda_3 \ln M + \ln V + \mu, \quad (9)$$

where

$$P = \sum_{i=1}^3 S_i P_i, \quad S_i = \frac{Q_i}{Q}, \quad i = 1, 2, 3,$$

the λ_i 's are parameters to be estimated, and μ is the error term. Costs of capital are not included because no adequate data are available.

The two fuel-split equations follow Eqs. (4a) and (4b) and are specified explicitly by

$$\ln \frac{S_1}{S_3} = \alpha_0 + \alpha_1 \ln P_1 + \alpha_2 \ln P_2 + \alpha_3 \ln P_3 + v, \quad (10a)$$

$$\ln \frac{S_2}{S_3} = \beta_0 + \beta_1 \ln P_1 + \beta_2 \ln P_2 + \beta_3 \ln P_3 + w, \quad (10b)$$

where the α_i 's and β_i 's are parameters to be estimated, and v and w are the error terms.

As indicated above, if only the fuel-split equations are considered, then OLS estimation attains efficiency. However, for the entire system including both aggregate demand and fuel-split equations, asymptotic efficiency requires consideration of the covariance between aggregate demand and fuel-split equations. The generalized least-squares (GLS) procedure developed by Zellner for a set of seemingly unrelated regression equations provides such a procedure.¹¹

By employing this approach, the results in Table 3 were developed using annual state-level data obtained from the U.S. Bureau of the Census for two recent census years, 1971 and 1974.¹² Note, however, that consistent and complete data were available for only 19 states in 1971 and 10 states in 1974.* The model was first estimated for 1971 and 1974 separately. But the results for 1974 are poor in that several estimated coefficients have the unexpected sign. The results for 1971 are much better, with all estimated coefficients having the expected sign whenever they could be determined a priori, but the estimated standard errors are high for several variables.

* Several states where coal was not used were excluded. Also, there are numerous states where data were withheld by the Bureau of the Census to avoid disclosing figures for individual companies. These represent severe data limitations for this study.

Table 3. Estimated aggregate demand and fuel-split equations^a

Equation	Dependent variable	Energy price $\ln P$	Oil price $\ln P_1$	Natural gas price $\ln P_2$	Coal price $\ln P_3$	Value added $\ln V$	Wage rates $\ln W$	Material costs $\ln M$	Constant	R ²	N
<u>Pooled 1971 and 1974</u>											
Aggregate demand	$\ln Q$	-1.438 (0.37)				0.927 (0.14)	1.639 (0.72)	1.003 (0.57)	8.402 (1.10)	0.59	29
Oil/coal	$\ln(S_1/S_3)$		-2.772 (0.67)	2.305 (1.14)	3.344 (1.04)				2.338 (0.54)	0.53	29
Gas/coal	$\ln(S_2/S_3)$		1.708 (0.58)	-2.114 (0.96)	2.655 (0.89)				-0.220 (0.48)	0.17	29
<u>1971</u>											
Aggregate demand	$\ln Q$	-0.863 (0.86)				0.961 (0.16)	2.422 (1.26)	1.147 (0.68)	7.459 (1.48)	0.68	19
Oil/coal	$\ln(S_1/S_3)$		-4.188 (1.55)	2.397 (1.32)	3.115 (1.50)				1.815 (0.89)	0.59	19
Gas/coal	$\ln(S_2/S_3)$		0.627 (1.26)	-2.534 (1.10)	3.498 (1.34)				-0.658 (0.81)	0.35	19

^aThe figures in parentheses are estimated standard errors, R² is the squared correlation coefficient between the actual and estimated values of the dependent variable and N is the number of observations.

Thus, the model was also estimated using pooled data for 1971 and 1974. The resulting estimates are improved; the estimated standard errors for several variables are substantially smaller than the estimates of either 1971 or 1974. The GLS estimates of Eqs. (9), (10a), and (10b) for 1971 and for pooled 1971 and 1974 are presented in Table 3. All fuel prices were deflated by the wholesale price index into 1971 dollars.

From Table 3, the following results are observed:

1. Energy price, wage rates, material costs, and value added are all statistically important determinants of aggregate energy demand in the paper industry in that the estimated elasticities all have *t*-ratios greater than 2.0.

2. In the fuel-split equations, the magnitudes of the estimated fuel-price coefficients differ substantially. Furthermore, the "third-price" coefficients (which the Baughman and Joskow model would force to zero) are statistically significant in both fuel-split equations in the pooled model. The results support the earlier arguments that price coefficients should not be constrained as in the Baughman and Joskow model unless additional justification can be provided.

5. ENERGY DEMAND ELASTICITIES

Because the model was estimated essentially from cross-sectional data, elasticities derived from the estimated coefficients may be interpreted as long-run elasticities. The estimated aggregate demand equations (Table 3) show that the aggregate price elasticities are -1.438 for the pooled model and -0.963 for the 1971 model. The results suggest that the aggregate demand is responsive to price changes, especially because the estimate from

pooled model, using a larger sample, is more reliable than that estimated for 1971 alone. The aggregate demand represented in the model, however, includes only the three purchased boiler fuels and does not include the recovery fuels such as spent liquor and bark. Increases in the prices of purchased fuels may induce an increase in the demand for recovery fuels. In fact, this phenomenon seems to have occurred. Data compiled by the American Paper Institute show that the total purchased fuels declined from 1173×10^9 Btu in 1972 to 1043×10^9 Btu in 1976 as energy prices increased. However, the use of bark and spent liquor increased from 896×10^9 Btu to 925×10^9 Btu for the same period. Thus, one would expect the aggregate price elasticity for total energy use (purchased plus recovery fuels) to be smaller than estimated in the model.

Consider next the market share elasticities. As shown in Eqs. (8a), (8b), and (8c), share elasticities depend upon shares and structural parameters. Because share elasticities are linear functions of the estimated parameters, their standard errors can be computed. By using Eq. (8a), for example, the variance of the estimated share elasticities can be computed by

$$V(E_{3j}) = S_1^2 V(\beta_{13j}) + S_2^2 V(\beta_{23j}) + 2S_1S_2 \text{cov}(\beta_{13j}, \beta_{23j}) ,$$

where the variance and covariance of the estimated structural coefficients are available from the regression results. The estimated standard error is obtained simply by taking the square root of the estimated variance.

By using the sample means in Table 4, the market share elasticities and their estimated standard errors shown in Table 5 were computed. The results based on the 1971 model show that all market share elasticities

Table 4. Sample means of market shares and prices of boiler fuels

Variable	Fuel	1971	1971 and 1974
<i>Market share</i>			
S_1	Fuel oil	0.340	0.336
S_2	Natural gas	0.349	0.330
S_3	Coal	0.311	0.334
<i>Fuel price (\$/10⁶ Btu)^a</i>			
P_1	Fuel oil	0.801	1.074
P_2	Natural gas	0.662	0.676
P_3	Coal	0.663	0.699

^aIn 1971 constant dollars.

Table 5. Estimated market share elasticities

Fuel share	Oil price	Natural gas price	Coal price
<u>1971 model</u>			
Fuel oil	-2.545 (0.832) ^a	2.466 (0.711)	0.835 (0.804)
Natural gas	1.016 (0.662)	-2.465 (0.573)	1.128 (0.706)
Coal	1.643 (0.868)	0.069 (0.745)	-2.280 (0.872)
<u>Pooled model</u>			
Fuel oil	-1.283 (0.378)	2.255 (0.643)	1.348 (0.586)
Natural gas	-0.219 (0.332)	-2.164 (0.542)	0.659 (0.505)
Coal	1.489 (0.465)	-0.050 (0.617)	-1.996 (0.564)

^aThe figures in parentheses are estimated standard errors.

have the expected sign. The own-price elasticities are all greater than 2.0 in absolute value and statistically significant at the 1% level. Estimated cross-price elasticities have, for the most part, a large magnitude and vary considerably among fuels. The estimated share elasticity of coal with respect to natural gas price is not statistically different from zero. The results for the pooled model show a very similar pattern to the results of the 1971 model except that most estimated elasticities are somewhat smaller in magnitude. Even though two estimated cross-price elasticities have the unexpected sign, they are not statistically significant.

The pattern of the estimated cross-price elasticities suggests that (1) natural gas price has little impact on the share of coal and (2) the prices of oil and coal have much smaller effects on the share of natural gas when the 1974 data were added in the pooled model. A careful examination of the nature of boilers and of the recent energy situation gives a satisfactory explanation of these phenomena. First, fuel switching between natural gas and oil is much easier than between gas and coal or between oil and coal. It is difficult and costly to convert gas and oil boilers into boilers that burn coal. This may explain why the price of natural gas has a much stronger effect on the share of oil than on that of coal. Second, natural gas has become less readily available since 1971. The uncertainty about the supply of natural gas would have prevented paper mills from switching from oil and coal to natural gas, even though natural gas is relatively cheaper.

Considering the effects of individual fuel prices on aggregate demand, we can calculate the aggregate demand elasticities with respect to fuel prices. These elasticities (E_j) are expressed as

$$E_j = \lambda_1 \left(\sum_{i=1}^3 P_i S_i E_{ij} + S_j P_j \right),$$

where

λ_1 = estimated coefficient of P in Eq. (9) ,

E_{ij} = market share elasticities of fuel j with respect to the price of fuel i .

Using the sample means in Table 4, the estimated λ_1 in Table 3, and the estimated market share elasticities in Table 5, we computed the aggregate demand elasticities with respect to fuel prices (Table 6). Aggregate demand elasticities are nonlinear functions of the estimated structural parameters, and their standard error estimates cannot be easily obtained. The results show that all three elasticities have a negative coefficient, suggesting that an increase in any of the prices of boiler fuels would reduce the demand for total purchased fuels. Furthermore, the price of natural gas appears to have a stronger impact on aggregate demand than do the prices of oil and coal. The elasticity with respect to oil price is the lowest among the three. These results hold for both the 1971 and pooled models, although the estimated elasticities for the pooled model are all greater in absolute value than those computed for the 1971 model. The difference may be due to conservation measures adopted during the oil embargo in 1973-1974. If voluntary measures of energy conservation were widely implemented, the estimated aggregate price elasticities for the pooled model would be biased upward and the true elasticities would be smaller.

Table 6. Estimated aggregate demand elasticities

Model	Oil price	Natural gas price	Coal price
1971	-0.106	-0.317	-0.207
Pooled 1971 & 1974	-0.284	-0.752	-0.568

It is also of interest to compute the conventional demand elasticities for individual boiler fuels. Because the demand for individual fuels is given by $Q_i = S_i Q$, the conventional demand elasticities can be expressed by

$$L_{ij} = E_j + E_{ij},$$

where L_{ij} is the elasticity of the demand for fuel i with respect to the price of fuel j and E_j and E_{ij} are aggregate demand and market share elasticities respectively. Table 7 presents the estimated conventional demand elasticities. The major findings are summarized below

1. The results show that all own-price elasticities are considerably greater than unity. These high price elasticities result from the fact that boiler fuels are generally fairly substitutable (with the qualifications discussed later).

2. The estimated cross-price elasticities are nonsymmetrical. The price of natural gas appears to have a strong effect on the demand for fuel oil. This may be due to the easy switching between the two fuels. The price of oil, though, has little effect on natural gas demand. In fact, the cross-price elasticity of natural gas demand with respect to oil price in the pooled model is negative. However, this negative cross-price elasticity is likely to be statistically insignificant because the estimated

Table 7. Estimated conventional demand elasticities

Fuel	Oil price	Natural gas price	Coal price
<u>1971 model</u>			
Fuel oil	-2.651	2.149	0.628
Natural gas	0.910	-2.782	1.101
Coal	1.537	-0.248	-2.487
<u>Pooled model</u>			
Fuel oil	-1.567	1.503	0.780
Natural gas	-0.503	-2.916	0.091
Coal	1.205	-0.802	-2.564

market share elasticity as a subcomponent is statistically insignificant (Table 5). The small effect of oil price on gas demand could be explained by the fact that the demand for natural gas was not determined solely by relative fuel prices. The unavailability of natural gas prevented its share from growing, even though its price was low. The shortage of natural gas affected the industrial sector more than the residential and commercial sectors, and the price-quantity relationship was likely to be distorted when shortages occurred. In fact, the implausible estimates of the cross-price elasticities (i.e., incorrect sign) are all associated with natural gas. These results clearly point to the need to deal with the availability of natural gas; an attempt is underway to construct suitable data on natural gas availability from the curtailment data recently compiled by the Federal Energy Administration (now under the Department of Energy).¹³

3. In the case between coal and oil, the estimated cross-price elasticity for coal demand is much higher than that for oil demand. This

may result from the fact that it is much easier to convert a coal boiler to oil than to convert an oil boiler to coal.

6. CONCLUDING REMARKS

In this report, a generalization of the Baughman and Joskow model is presented. It is shown that their constraints need not be imposed to determine uniquely all demand elasticities in a logically consistent manner. Thus, the general model adds needed flexibility to the approach used by Baughman and Joskow without complicating empirical estimations.

The general model is applied to estimating the energy demand and choice of boiler fuels in the pulp and paper industry (SIC-26). Even though only a small sample (a total of 29 observations in the pooled 1971 and 1974 model) was used, the results support the theoretical justification of the general model. Some of the improper coefficients estimated are due to the peculiar characteristics of the market conditions. Specifically, the availability of natural gas and the uncertainty of its supply appear to have distorted the usual quantity and price relationships. Further research is necessary to cope with this dynamic and unbalanced situation in the natural gas market.

Despite these problems in estimation, the following enlightening results are observed:

1. Aggregate demand for purchased boiler fuels in the paper industry is responsive to changes in energy prices.
2. The market shares of boiler fuels are highly dependent upon their prices; the own-price elasticities are all considerably greater than unity. These results, along with several large cross-price elasticities, suggest

that the possibility of interfuel substitution is rather strong in the paper industry. However, this assertion cannot be made without one qualification, namely, that the unavailability of natural gas may discourage the industry from switching to natural gas even though its price is kept lower than what would result in a competitive situation.

3. The results also suggest that the aggregate demand for purchased boiler fuels would probably be reduced if any of their prices increase. However, the purchased fuels are likely to be substituted by the recovery fuels, such as spent liquor and bark. It remains to be investigate whether or not the total energy demand would be reduced as a result of increases in the prices of purchased fuels.

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APPENDIX

A DYNAMIC FORMULATION

This appendix presents the dynamic version of a generalization of the Baughman and Joskow model. To begin with, it seems reasonable to postulate a common log-linear demand equation,

$$q_{it}^* = A_i^* P_{1t}^{\beta_{i1}^*} P_{2t}^{\beta_{i2}^*} P_{3t}^{\beta_{i3}^*} \prod_{k=1}^K X_{kt}^{\gamma_{ik}^*},$$

where q_{it}^* is desired demand at time t and X_t represents other variables such as income and nonpecuniary factors that may be important. Now suppose, as do Baughman and Joskow, that rigidities resulting from durable goods prevent complete adjustment to desired consumption levels, and, instead, adjustment (for all energy forms) follows the familiar equation

$$q_{it} = q_{it-1}^\delta (q_{it}^*)^{1-\delta}, \quad 0 < \delta < 1,$$

where q_{it} is actual consumption of energy form i at time t . In this framework, the logarithm of the ratio of shares between any two energy forms at time t is

$$\begin{aligned} \ln\left(\frac{S_{it}}{S_{jt}}\right) &= \ln\left(\frac{q_{it}}{q_{jt}}\right) = \ln\left(\frac{A_i^*}{A_j^*}\right)^{1-\delta} + \sum_{p=1}^3 (\beta_{ip}^* - \beta_{jp}^*) \ln P_{pt} \\ &\quad + \sum_{k=1}^K (\gamma_{ik}^* - \gamma_{jk}^*) \ln X_{kt} + \delta \ln\left(\frac{q_{it-1}}{q_{jt-1}}\right) \\ &= \alpha_{ij} + \sum_{p=1}^3 \beta_{ijp} \ln P_{pt} + \sum_{k=1}^K \gamma_{ijk} \ln X_{kt} \\ &\quad + \delta \ln\left(\frac{S_{it-1}}{S_{jt-1}}\right), \end{aligned} \tag{11}$$

where

$$\alpha_{ij} = \ln A_{ij} \equiv \ln \left(\frac{A_i^*}{A_j^*} \right)^{1-\delta},$$

$$\beta_{ijp} = \beta_{ip}^* - \beta_{jp}^*,$$

$$\gamma_{ijk} = \gamma_{ik}^* - \gamma_{jk}^*.$$

The model in Eq. (11) is the same as Baughman and Joskow's except that all prices are included and long-run cross-price elasticities are clearly unrestrained. Short-run cross-price elasticities are constrained to some extent because δ , or the rate of adjustment, does not vary with respect to energy form. Baughman and Joskow also imposed this assumption. It can be relaxed but only at the expense of losing the convenience of Eq. (11). Rather than containing a simple lag in the ratio of shares, the equation would include separate lags on quantities of both energy forms used in the ratio.

Using the same approach in examining symmetry as above, Eq. (11) implies (for simplicity, only one X_k is employed, and it is denoted as X hereafter) that

$$S_1 = A_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} \left(\frac{S_{1t-1}}{S_{3t-1}} \right)^{\delta} S_3, \quad (12)$$

$$S_2 = A_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} \left(\frac{S_{2t-1}}{S_{3t-1}} \right)^{\delta} S_3, \quad (13)$$

where the time subscript t is dropped from all the variables except when $t-1$ appears. Substituting Eq. (12) and Eq. (13) into the identity $S_1 + S_2 + S_3 = 1$ and solving for S_3 yields

$$S_3 = \left[1 + A_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} (S_{1t-1}/S_{3t-1})^\delta + A_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} (S_{2t-1}/S_{3t-1})^\delta \right]^{-1} \quad (14)$$

Now, substituting Eq. (14) into Eq. (12), for example, obtains

$$\begin{aligned} S_1 &= \left[1 + A_{13}^{-1} P_1^{-\beta_{131}} P_2^{-\beta_{132}} P_3^{-\beta_{133}} X^{-\gamma_{13}} (S_{3t-1}/S_{1t-1})^\delta + \frac{A_{23}}{A_{13}} P_1^{\beta_{231}-\beta_{131}} P_2^{\beta_{232}-\beta_{132}} P_3^{\beta_{233}-\beta_{133}} X^{\gamma_{23}-\gamma_{13}} (S_{2t-1}/S_{1t-1})^\delta \right]^{-1} \\ &= \left[1 + A_{31} P_1^{\beta_{311}} P_2^{\beta_{312}} P_3^{\beta_{313}} X^{\gamma_{31}} (S_{3t-1}/S_{1t-1})^\delta + A_{21} P_1^{\beta_{211}} P_2^{\beta_{212}} P_3^{\beta_{213}} X^{\gamma_{21}} (S_{2t-1}/S_{1t-1})^\delta \right]^{-1}, \quad (15) \end{aligned}$$

where

$$\left. \begin{aligned} A_{31} &= A_{13}^{-1}, \\ \beta_{31p} &= -\beta_{13p}, \quad p = 1, 2, 3, \\ \gamma_{31} &= -\gamma_{13}, \\ A_{21} &= A_{23}/A_{13}, \\ \beta_{21p} &= \beta_{23p} - \beta_{13p}, \quad p = 1, 2, 3, \\ \gamma_{21} &= \gamma_{23} - \gamma_{13}. \end{aligned} \right\} \quad (16)$$

Similar to the static model, symmetry is attained without imposing additional constraints on the parameters already defined. The short-run elasticities under this dynamic formulation can be determined by calcu-

lating $\partial S_i / \partial P_j$ while holding lagged values of shares in Eqs. (15) and (16) fixed. The resulting expressions are the same as Eqs. (8a), (8b), and (8c).

To calculate long-run elasticities, one can first solve Eqs. (12) and (13) for long run equilibrium shares, which yields

$$S_1 = \left[A_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} \right]^{1/(1-\delta)} S_3, \quad (17)$$

$$S_2 = \left[A_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} \right]^{1/(1-\delta)} S_3, \quad (18)$$

where $0 < \delta < 1$. Substituting Eq. (17) and Eq. (18) into the identity obtains

$$S_3 = \left[1 + \left(A_{13} P_1^{\beta_{131}} P_2^{\beta_{132}} P_3^{\beta_{133}} X^{\gamma_{13}} \right)^{1/(1-\delta)} + \left(A_{23} P_1^{\beta_{231}} P_2^{\beta_{232}} P_3^{\beta_{233}} X^{\gamma_{23}} \right)^{1/(1-\delta)} \right]^{-1}. \quad (19)$$

In this case, substituting (19) into (17) produces

$$\begin{aligned} S_1 = & \left[1 + \left(A_{13}^{-1} P_1^{-\beta_{131}} P_2^{-\beta_{132}} P_3^{-\beta_{133}} X^{\gamma_{13}} \right)^{1/(1-\delta)} + \left(\frac{A_{23}}{A_{13}} P_1^{\beta_{231}-\beta_{131}} P_2^{\beta_{232}-\beta_{132}} P_3^{\beta_{233}-\beta_{133}} X^{\gamma_{23}-\gamma_{13}} \right)^{1/(1-\delta)} \right]^{-1} \\ & - \left[1 + \left(A_{31} P_1^{\beta_{311}} P_2^{\beta_{312}} P_3^{\beta_{313}} X^{\gamma_{31}} \right)^{1/(1-\delta)} + \left(A_{21} P_1^{\beta_{211}} P_2^{\beta_{212}} P_3^{\beta_{213}} X^{\gamma_{21}} \right)^{1/(1-\delta)} \right]^{-1}, \end{aligned} \quad (20)$$

where new parameters are defined by Eq. (16). A similar equation can obviously be developed for S_2 as well using Eq. (18). At this point, one

can note more clearly that the Baughman and Joskow concept of consistency is satisfied in the long run without imposing constraints.

To find long-run elasticities for S_3 , Eq. (19) can be used to determine that

$$\begin{aligned}\frac{\partial S_3}{\partial P_j} &= -S_3^2 \left[\frac{\beta_{13j}}{(1-\delta)P_j} \frac{S_1}{S_2} + \frac{\beta_{23j}}{(1-\delta)P_j} \frac{S_2}{S_3} \right] \\ &= -\frac{S_3}{(1-\delta)P_j} \left[\beta_{13j} S_1 + \beta_{23j} S_2 \right]\end{aligned}$$

Hence, the long-run elasticities of S_3 with respect to prices are

$$\begin{aligned}\bar{E}_{3j} &= -\frac{1}{1-\delta} (\beta_{13j} S_1 + \beta_{23j} S_2) \\ &= E_{3j}/(1-\delta), \quad j = 1, 2, 3.\end{aligned}$$

Similarly, long-run elasticities for other shares have the same relationships with short-run elasticities; thus

$$\bar{E}_{ij} = E_{ij}/(1-\delta), \quad i, j = 1, 2, 3,$$

where E_{ij} is defined earlier.

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