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Electricity Demand
in Primary Aluminum Smelting

by

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ABSTRACT

The demand for electricity by primary aluminum smelters is estimated econometrically. Cross section data is used, including plant data for the U.S. and Norway and a national average for Japan. The data are sampled for two periods, one before and one after the 1973-74 energy price increase. The paper estimates the elasticity of substitution between electricity and an aggregate of all other inputs, assumed to exist. The estimated value of 0.1 is low, but significantly different from zero. Large price increases, such as the equalization of hydro and other power prices are found to result in substantial energy savings.

1. Introduction

Aluminum is one of the giant energy users among the manufacturing industries. The most energy intensive stage is the reduction of alumina to primary metal. This is done by an electrolytic process, which requires 13-19 kwh direct current electricity per kilogram aluminum. Up to recently, a substantial part of the aluminum smelting industry has been able to obtain electric power at very low cost, especially in areas with abundant hydro power, such as Canada, Norway, and the Pacific Northwest of the U.S. With increasing scarcity of all energy, this is in the process of changing, and the possibilities of energy conservation in this industry are of obvious concern to policy makers as well as to the industry itself.

Some attention seems to have been devoted to this problem in the engineering literature1); econometric estimation techniques seem, however, not to have been used. This paper presents an attempt to estimate econometrically the demand for electricity in primary aluminum smelting as a function of relative prices. From an econometric point of view, this industry is an attractive case to study because it produces a homogeneous output with a well-defined set of inputs, which allows fairly direct application of the economic theory of production. A number of econometric studies have already estimated factor demand in manufacturing industries, but mostly on higher levels of aggregation2). It seems timely to supplement these efforts with micro estimation of a single industry with a homogeneous output.

The price that has to be paid for working on the micro level is that data are available only for a subset of all plants and only for one input, electricity. This limited data is nevertheless used in the present paper to estimate the elasticity of substitution between electricity and an aggregate of other inputs. The focus is on long-run equilibrium relationships, which may be thought of in this context as the ex ante isoquant of a putty-clay technology[3]. The core of the data used to estimate this is taken from a cross section of plants in the U.S. and a Japanese national average from the 1973-74 period, before the impact of the OPEC oil price increase was felt. This core of data is supplemented with data from the same cross-section in 1977-78. A cross-section of Norwegian plants is also included in the full sample, with price data for 1973 and 1978 and quantity data for 1978. An ad hoc partial adjustment mechanism is used for estimation with observations from different dates.

The possibilities for substitution between electricity and other inputs to aluminum reduction are found to be somewhat limited. The elasticity of substitution is found to be around 0.1. It is, however, significantly different from zero. Moreover, the results indicate a large potential of energy conservation for large increases in electricity prices, such as are being considered in Norway and in the Pacific Northwest of the U.S. It is less clear how long time would be needed to obtain this effect. A different kind of sample as well as a better dynamic theory is needed to give good and meaningful estimates of speeds of adjustment.

Section 2 presents the mathematical model of the technology and discusses some problems of price uncertainty. A discussion of the data is given in section 3. Section 4 presents the econometric formulation of the model and section 5 the results. Section 6 concludes.

2. Technology Model

Write the production possibility constraint for aluminum reduction as

$$A \geq F(E, X_1, \ldots X_n), \tag{1}$$

where A is aluminum output, E is electricity input, and $X_1, \ldots, X_n$ are other inputs. Assume F to be homogeneous of degree one and concave. Ideally, one would want price and quantity data for all variables in (1) for estimation of factor demand in aluminum smelting. In practice, data are available for output and electricity only. Estimation on the basis of these data can be made under the following assumption:

F is separable between E and $X_1, \ldots, X_n$ so that other inputs can be represented by a single aggregate. Denote this aggregate as the scalar X. (1) can then be written

$$A \geq F(E, X(X_1, \ldots, X_n)). \tag{1'}$$

Assume further that F is CES in E and X:

$$A \geq \gamma [\delta E^{(\sigma-1)/\sigma} + (1-\delta) X^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)}, \tag{2}$$

where σ is the elasticity of substitution. For fixed output and electricity prices, profit maximization gives

$$E/A = c\,(P_E/P_A)^{-\sigma}. \tag{3}$$

(3) can obviously be estimated with price and quantity data for output and electricity input only.

For an important part of the data sample, the customers of Bonneville Power Administration (BPA) in the Pacific Northwest of the U.S., a slight modification of (3) is necessary. The power supply from BPA is based on hydro generation and depends on the level of precipitation. All contracts with aluminum customers are interruptible. At the times when BPA cannot deliver from its own sources, it acts as a trustee for the industry buying replacement power in the open market. Industry firms then have the option of purchasing this power or temporarily reducing their operation. In this situation, the marginal price of electricity depends on the firm's demand for electricity and on the weather, which is stochastic. Write this as

$$p_E = p_E(E,\xi)^{4)},$$

where ξ is a stochastic parameter.

Assume that the choice of electricity intensity is made before the realization of ξ is known and is derived from expected profit maximization. Denote electricity intensity by e, relative intensity of other factors by x, and factor prices relative to output prices by p_E and p_x. Use aluminum output as numéraire (this is implicit in (3)), and consider maximization of normalized expected profit

$$(4)\quad \Pi = [F(eA,\ x\ A)] - \int_0^{Ae} p_E(Ae',\ \xi)\,d(Ae') - (p_x\ x\ A).$$

The first order condition for energy intensity is obtained from

$$\frac{\partial \Pi}{\partial e} = F_E(e) \quad (A) - (Ap_E(Ae))$$

$$= F_E(e)\bar{A} - \bar{p}_E\bar{A} - \text{cov}(A,p_E) = 0, \text{ or}$$

$$(5) \qquad e = F_E^{-1}[\bar{p}_E + \text{cov}(A/\bar{A},\ p_E)],$$

where F_E^{-1} is a decreasing function in its single argument.

Obviously, the covariance term is non-positive so that

$$e \geq F_E^{-1}(\bar{p}_E).$$

Random movements in p_E resulting from fluctuations in the price of aluminum are common for all observations and are essentially captured by the constant term in (3). Ignoring this reduces the distribution of p_E to a two-point distribution (Bonneville either does or does not meet all demand). Then it is easy to show that the argument of F_E^{-1} in (5) is greater than Bonneville's price (p_B), so that

$$e < F_E^{-1}(p_B).$$

Thus, actual demand lies in the interval

$$F_E^{-1}(\bar{p}_E) \leq e < F_E^{-1}(p_B).$$

The intuitive meaning of the second inequality is fairly obvious: Since the marginal price of electricity is higher than Bonneville's price some of the time, it would be wasteful to act as if all electricity could be gotten at the lower price. The first inequality is more subtle. It may help the understanding to note that it would have been an equality if output were exogenous. However, firms may respond to temporarily high electricity prices by reducing output. Then, acting as if the expected price of electricity were given with certainty would add unnecessary costs of other factors.

For estimation, the argument of F_E^{-1} in (5) may be calculated and used as the "price" for Bonneville customers. In this paper, the covariance term is estimated by assuming that output is 10% lower whenever replacement power is purchased. The method for estimating the probability of this event is described in the Data Appendix.

The separability assumption in (1') imposes some important constraints that may be rejected by tests based on data on all inputs. For example, it rules out complementarity between electricity and other factors, such as capital. As is well known, energy-capital complementarity has been found in many industry studies on higher levels of aggregation5). Also, it allows for interfuel substitution only via the aggregate X. With the presently available data, however, these problems cannot be dealt with.

Technical progress is not treated explicitly. It is sometimes argued that improvements in energy efficiency in aluminum reduction is a question of technical progress only and has little to do with prices. According to this view, the less energy-efficient smelters, such as the majority of the plants in the Pacific Northwest of the U.S., use more electricity only because they are older and less modern. This argument overlooks, however, important aspects of the economics of technical progress. The majority of technical improvements in aluminum reduction do not seem to have been of the type that permits reduction of all factor intensities. Rather, they have expanded the production possibility set by permitting more substitution away from energy. Over time, only plants with high electricity prices have had the incentive to install newly invented electricity saving equipment. Thus, in long-run equilibrium, factor intensities are distributed along the new long-run isoquant as predicted by economic theory. Introducing plant age as an additional explanatory variable would introduce a risk of cluttering up important economic relationships.

3. Data

The data cover a cross-section of reduction plants in the U.S., Japan, and Norway. All of the Norwegian observations represent single plants. So do most of the U.S. observations, except for the plants of Alcoa, Kaiser, and Reynolds in the Pacific Northwest. For each of these, the data are averages for two plants. The Japanese observations are national averages. The sample is not random, but consists of those units for which data are available. A complete listing of all the observed units is in the Data Appendix.

It was considered desirable to have data for two years, one before and one as late as possible after OPEC's oil price increase in 1973-74. 1973 was considered the best candidate for the former period. There was, however, a problem of getting quantity data for the U.S. observations for 1973. The available quantity data for the U.S. give consumption of electricity and productive capacity by plant. If aggregate capacity utilization is close to 100%[6)], this can be served as a proxy for plant output and be used for computation of electricity intensity. However, aggregate capacity utilization for the U.S. in 1973 was as low as 93%. On the other hand, the corresponding rate for 1974 was close to 100%. It may be assumed that, for technical reasons, electricity intensities could not be changed very much from 1973 to 1974. Nor did, for that matter, electricity prices change very much for the plants in the present sample, because hydro and coal are the dominant energy sources. On this background, I decided to couple 1973 price data with 1974 quantity data for the U.S. Since capacity utilization in the U.S. was reasonably close to 100% in 1978 as well, quantity as well as price data were used for that year also.

For Japan, annual data 1973-77 are available, of which price data for 1973, quantity data for 1974, and price and quantity data for 1977 are used in the estimations. For Norway, quantity data are available for 1978 only. These are used together with price data for 1973 and 1978.

The data sources are as follows. All the Japanese data were obtained from The Insitute of Energy Economics, Tokyo. The Japanese electricity price data are national averages for industrial customers. I adjusted these as explained in the Data Appendix. The Norwegian quantity data were obtained from industry sources (made available by the Institute of Industrial Economics, Norway). Norwegian price data were abstracted from public documents of Stortinget (the Norwegian Parliament).

Production data for the U.S. were taken from plant capacity figures, partly published by the U.S. Bureau of Mines and partly provided by industry sources. The capacity data were supplemented with aggregate production and capacity data for the Pacific Northwest and the country as a whole, made available by Bonneville Power Administration. Electricity consumption data were provided by Bonneville Power Administration and

Tennessee Valley Authority for their customers. For the remaining observations, the data were extracted from Statistics of Privately owned Electric Utilities in the U.S., an annual publication of the Federal Power Commission, and from publicly available forms filed with federal and state energy regulatory commissions. All electricity consumption data include auxiliary power as well as DC current used in the electrolytic process.

About half of the plants in the U.S. sample do primary smelting only. For the other half, the electricity consumption data cover fabrication plants at the same location. Information as to which smelting plants are combined with fabrication plants was obtained from industry sources; it was not possible, however to get specific data for smelting. This problem was essentially solved with a dummy variable, as explained in the next section.

Electricity price data were obtained from similar sources as the quantity data. The price data for the Pacific Northwest permitted computation of the average price of replacement power as well as Bonneville's average price. The probability of the event that replacement power is used was computed from monthly data on use of replacement power by company for 1973-78. Together with the assumption suggested in section 2 above, this permitted computation of the argument of F_E^{-1} in (5). The computed price of replacement power for 1978, 65.5 mills/kwh, seems unreasonably high. A price of 25 mills was assumed; all regressions were, however, run with both values.

Aluminum price data were taken from <u>Metal Statistics</u>, an annual publication of Metallgesellschaft Aktiengesellschaft, supplemented by news releases of the U.S. Bureau of Mines for 1978. The Japanese price was assumed equal to the U.S. price plus shipping cost from the West Coast of the U.S., obtained directly from shipping sources. The Norwegian price was assumed equal to the U.K. price less 1.3% transportation cost. Currencies are converted according to average actual exchange rates for the respective years, which is reasonable for a traded commodity.

A priori, the U.S. data for 1973-74 seem the most accurate, because the quantity data are quite good (capacity utilization is practically 100%), and because the prices are realistic marginal prices. Furthermore, 1973 seems to have been a year of approximate long-run equilibrium in factor markets for the U.S. aluminum industry. Mostly the same can be said about the Japanese data for the same period, except that the price figure is more uncertain.

The 1977-78 data are, of course, uncertain, because long-run equilibrium cannot be assumed. In addition, U.S. quantity data are somewhat uncertain because of the lower capacity utilization rate (96% in and 97% outside the Pacific Northwest for the present sample). The Japanese price figure for 1977 is uncertain like the one for 1973. The Norwegian quantity data for 1978 may represent engineering ideals rather than actual behavior. The price data for Norway may be somewhat unrealistic because, for some contracts, it is not clear (to this author) whether or not the companies have to pay for the whole contracted amount of electric energy regardless of actual usage. This is especially true of older contracts. Neither is it clear whether additional power can be purchased. Thus, the effective marginal price may be both higher and lower than the ones recorded. The results in section 5 are interpreted with these weaknesses in mind.

A detailed account of the data is given in the Data Appendix.

4. Econometric Formulation

Consider first cross-section estimation with data for 1973-74 only. Writing (3) in logarithmic form and adding terms to account for fabrication and stochastic disturbances gives the estimation equation

$$y'_i = \alpha - \sigma x'_i + \beta_i z'_i + \varepsilon'_i. \tag{6}$$

Here, y'_i is the log of electricity consumption per unit of output, x'_i is the log of the price ratio (redefined as in (5) wherever necessary), z'_i is a dummy variable for fabrication, and ε'_i is a random disturbance. The dummy variable z'_i has the value 1 when the observation covers one smelting plant and one fabrication plant or two smelting plants and two fabrication plants; it is 0.5 for two smelting plants and one fabrication plant, and 0 otherwise.

The error term is assumed to be distributed independently across observations and with respect to x'_i, z'_i. It can be interpreted as the percentage deviation from the optimal electricity intensity. Its variance is assumed to be independent of plant size[7]. Some of the observations are, however, averages of two or more plants. We thus have, for all i

$$\varepsilon'_i = \sum_{j=1}^{n_i} \alpha_{ji} \varepsilon'_{ji},$$

where α_{ji} is the ratio of capacity in plant j to total capacity of all plants in observation i, and n_i is the number of plants in this observation. Assuming all ε'_{ji} to be independently and identically distributed normal variables with mean 0 and variance τ^2, gives

$$(7) \qquad \operatorname{var}(\varepsilon_i') = \sum_j \alpha_{ji}^2 \tau^2 .$$

Using one over the square root of the expression multiplying τ^2 in (7) as weights, (6) can be transformed to

$$(8) \qquad y_i = \alpha w_i - \sigma x_i + \beta_i z_i + \varepsilon_i ,$$

where w_i is the weight and ε_i is a regression error.

Note that the share of electricity going to fabrication, β_i, is assumed to vary from plant to plant. This is reasonable since fabrication plants vary in size and electricity intensity. β_i is assumed to be a random coefficient with mean $\bar{\beta}$ and uncorrelated with w, x, z, ε. Because β_i is random, (8) is not a regression equation. It can, however, be rewritten as

$$(9) \qquad y_i = \alpha w_i - \sigma x_i + \bar{\beta} z_i + (\beta_i - \bar{\beta}) z_i + \varepsilon_i .$$

Ordinary least squares applied to this equation would give unbiased, although inefficient estimates of α, σ, $\bar{\beta}$, because the error term, $(\beta_i - \bar{\beta}) z_i + \varepsilon_i$, is heteroskedastic. Letting δ^2 be the variance of β and λ the ratio of δ^2 to τ^2, its variance can be written as

$$\operatorname{var}[(\beta_i - \bar{\beta}) z_i + \varepsilon_i] = \delta^2 z_i{}^2 + \tau^2 = (\lambda z_i{}^2 + 1)\tau^2 .$$

The equation can be transformed again as

$$(10) \qquad (\lambda z_i^2 + 1)^{-1/2} y_i = (\lambda z_i^2 + 1)^{-1/2} (\alpha w_i - \sigma x_i + \bar{\beta} z_i + \varepsilon_i).$$

If λ were known, (10) would have been a regression equation. With λ unknown, the log likelihood function is (except for an inessential constant)

$$(11) \qquad L(\alpha, \sigma, \bar{\beta}, \tau^2, \lambda) = -\frac{n}{2} \ln \tau^2 - \frac{1}{2} \sum_i \ln(\lambda z_i^2 + 1)$$

$$- \frac{1}{2\tau^2} \sum_i (y_i - \alpha w_i + \sigma x_i - \bar{\beta} z_i)^2 / (\lambda z_i^2 + 1).$$

With λ as a parameter, (11) is maximized with respect to α, σ, $\bar{\beta}$, τ^2 by applying ordinary least squares to (10). The likelihood function can then be "concentrated" as

$$(12) \qquad L^*(\lambda) = -\frac{n}{2} \ln \tau^2(\lambda) - \frac{1}{2} \sum_i \ln(\lambda z_i^2 + 1) - \frac{n}{2}$$

$$= -\frac{n}{2} \ln(\sum_i e_i^2(\lambda)/n) - \frac{1}{2} \sum_i \ln(\lambda z_i^2 + 1) - \frac{n}{2},$$

where e_i is the OLS residual of (10); and likelihood can be maximized by search over λ. This procedure permits efficient estimation with standard econometric computer packages.

The observations for 1978 (1977 for Japan) are not assumed _a priori_ to represent a long-run equilibrium. Rather, the following _ad hoc_ partial adjustment model is postulated:

$$(13) \qquad y_i = \alpha w_i - \sigma(\Theta x_i + (1 - \Theta) x_{i,-1}) + \beta_i z_i + \varepsilon_i$$

$$= \alpha w_i - \sigma x_{i,-1} - \Theta\sigma\Delta x_i + \beta_i z_i + \varepsilon_i,$$

where $x_{i,-1}$ is the five year lagged relative price and Δx_i the five year increase[8)]. For the 1973 observations, x_i and $x_{i,-1}$ are assumed equal, implying $\Delta x_i = 0$. Θ may be interpreted as a five-year speed of adjustment, and $5/\Theta$ may serve as a measure of the number of years needed to reach the new long-run equilibrium.

As shown by Lucas (1967) and Treadway (1971) and further developed by Berndt, Fuss, and Waverman (1977), the partial adjustment model with a constant speed of adjustment has some very important shortcomings even for production models of the putty-putty type. In a putty-clay environment, which seems a good approximation for aluminum smelting, it is even harder to defend. It is used here as a simple method of making use of scarce data.

As noted in section 3, the U.S. quantity data for 1978 are less accurate than for 1974. This measurement error adds to the variance of the error term for these observations and calls for still another weighting of the data. The weights are estimated from the data as explained below.

5. Empirical Results

The results of estimation of (9) and (13) on the whole sample and various subsamples are presented in Table 1. Maximum likelihood estimation invariably gave the corner solution $\lambda = 0$. This is unreasonable, but may be explained by sampling variation. Likelihood ratio tests of the hypothesis $\lambda = 0.1$ gave χ^2 values between 0.5 and 1.1 -- highest for the smallest sample --, or well below the 5% critical value of 3.84. λ was then constrained to have this value. With the estimated values of $\bar{\beta}$ and τ, this means that fabrication plants on the same locations as smelters

Table 1

Estimation results for various samples.

Numbers in parenthesis are standard errors, bracketed numbers are t - statistics for the hypothesis that the parameter value is zero.

	U.S. 73-74	U.S.& Japan 73-74	U.S. 73-74 & 78	U.S.& Japan 73-74,77-78	Full sample
σ	0.09	0.10	0.10	0.12	0.13
	(0.06)	(0.04)	(0.04)	(0.03)	(0.03)
	[1.60]	[2.83]	[2.32]	[4.52]	[4.90]
$\bar{\beta}$	0.11	0.11	0.11	0.11	0.10
	(0.05)	(0.04)	(0.03)	(0.03)	(0.03)
	[2.33]	[2.53]	[3.11]	[3.39]	[3.27]
Θ	-	-	-0.05	0.28	0.31
			(0.78)	(0.40)	(0.32)
			[-0.06]	[0.70]	[0.97]
λ	0.1	0.1	0.1	0.1	0.1
τ	0.081	0.078	0.078	0.075	0.076
δ	0.026	0.025	0.025	0.024	0.024
Weights for U.S. '78 obs.	-	-	0.848	0.810	0.833
Sample size	15	16	30	32	38

typically are responsible for 8.5% to 13.5% of the power consumption of both plants. This seems well in accord with indirect evidence 9). Constraining λ to 0.1 causes only marginal changes in the other point estimates and standard errors.

The results in the first column of Table 1 are based on U.S. observations from before the impact of the 1974 oil price increase started to be felt. This part of the sample seems most reliable a priori and has large variation in the price variable, although a modest sample size of 15. The point estimate of σ, about 0.1, seems highly reasonable. It confirms the impression of limited substitution possibilities for electricity in primary aluminum smelting. It is sufficiently large, though, to indicate significant possibilities of energy conservation. For example, bringing electricity prices in the Pacific Northwest in line with the rest of the country (1973 prices) could eventually induce a saving of 2 billion kwh annually, or enough to light 2 cities of the size of Cambridge, Massachusetts.

The estimate of σ may be biased because of measurement errors or simultaneity. If so, the bias is downward. The bias is not likely to be large in this case, though. With the present data, the most serious measurement errors are likely to be found in the quantity data and thus to be absorbed in the error term of the equation. Any measurement errors in the price variable are likely to lie within a much smaller range than the variations in the price variable itself. Simultaneity is also less of a problem than in most demand studies, partly because electricity prices are set or regulated by government authorities, and partly because thermal generation of baseload power is done under non-decreasing returns to scale.

With the large price variation in the sample, one might have expected a tighter estimate of σ. For this sample, however, the random disturbances are sufficiently large to give a relatively high standard error of σ. This problem disappears when the sample is expanded to include the contemporaneous observation of the Japanese national average. The point estimate of σ is virtually unchanged, whereas its standard error is reduced by one third10). With an estimated t-statistic of 2.83 and a corresponding critical value of 2.13, its difference from zero is comfortably significant on the 5% level. The hypothesis that the technology is Cobb-Doublas ($\sigma=1$) is also rejected decisively with a t-value of -24.5. Some uncertainty is attached to the Japanese electricity price. Since some Japanese plants are hydro powered, the price used here may be too high, so that the estimates of σ and its standard error may be biased. This was checked by experimenting with various lower values of the Japanese electricity price variable. For values down to the level of TVA's price the point estimate of σ is increased, but only slightly. Its standard error increases a little more, but the t-statistic stays above 2.3. This seems strong evidence that the point estimate of 0.1 is indeed very robust.

This impression is confirmed by extending the sample to include the 1978 observations (1977 for Japan). The point estimate of σ changes only slightly and the confidence interval is tightened considerably. In these runs, the U.S. observations for 1978 are weighted to correct for the higher measurement error of the left hand side variable11).

The Norwegian price data may or may not be meaningful, as discussed above in section 3. As a superficial observation one may note, though, that the results improve rather than worsen when Norway is included in the sample (column 5 of Table 1). Also, a formal test ("Chow test") of the stability of the coefficients gives an F value with 3 and 30 degrees of freedom as low as 1.28 (5% critical value: 2.92). It may be noted, though, that five of the six Norwegian observations had positive residuals, which seems to indicate that the effective marginal electricity prices may have been somewhat lower.

The results are much less encouraging for the speed of adjustment, θ. Its standard error is large for all three samples, and its point estimate ranges from 0 to 0.3. Compared to the U.S., Japanese plants seem to have responded much more quickly to the increased electricity prices. The apparent improvement from including Norway in the sample is somewhat illusory, partly because no Norwegian quantity data for 1974 are available, and partially because the price of electricity actually declined relative to the price of aluminum for most of the companies.

With large standard errors for θ, the hypothesis of relatively quick adjustment cannot be rejected. However, the existing evidence, although weak, goes against it. In fact, total electricity consumption per kilogram aluminum (unadjusted for fabrication) increased by 1.2% from 1974 to 1978 in the U.S. sample. Aggregate figures from the Aluminum Association14) indicate a decrease of a similar magnitude, but it is not clear whether energy savings from recycling are included in this figure. How, then, can this apparent standstill be explained?

Environmental standards toughened in the U.S. as well as Japan over this period. This may explain some of the sluggishness, but hardly all of it. And it does not seem to explain the quicker response in Japan.

Since improvements in energy efficiency require investments, they may have been delayed because of general uncertainty about the future of the primary smelting industry in the Western world and Japan. For example, investments may not have been considered profitable if growth in aluminum production has been expected to come through recycling and from primary smelters in less developed countries[12)]. This points to a shortcoming of the partial adjustment model: the speed of adjustment is not constant but depends on the context of the change. Again, this may explain partly the low value of θ,but not the difference between the U.S. and Japan.

The third possibility is interfuel substitution. All energy prices increased after the 1974 oil price increase, but electricity based on coal and hydro increased relatively less than oil and natural gas[13)]. Thus, in attempts to cut total energy cost, electricity may have been given lower priority. This view seems in accordance with information from industry sources[14)]. It also seems capable of explaining some of the difference between the U.S. and Japan, because electricity production is based more extensively on oil in Japan. It is not captured by the present model, however, because the separability assumption, necessitated by the scarcity of data, does not capture interfuel substitution as a separate phenomenon.

With a value of θ close to zero for U.S. observations (column 3), including the observations for 1978 amounts to little more than a second drawing from the same sample. As is seen from the standard errors, this pays off in terms of increased efficiency.

The regressions in Table 1 were run with the assumed price of 25 mills/kwh for 1978 for replacement power in the Pacific Northwest of the U.S. None of the results were changed by using the computed price of 65.5 mills/kwh instead. This is hardly surprising as the weight assigned to 1978 prices is exactly the parameter Θ, which is very close to zero.

6. Concluding Remarks

An attempt has been done to estimate the demand for electricity in primary aluminum smelting. The attempt appears to have been successful. Data was collected for a cross-section of observations from the U.S., Japan, and Norway, all of which are leading suppliers of primary aluminum. The emphasis has been on long-run equilibrium relationships, with data from before the 1974 oil price increase as the core of the sample.

The elasticity of substitution between electricity and an aggregate of other inputs was estimated with a CES formulation of the technology model. The CES formulation implies a separability constraint which is quite restrictive but seems to have paid off in the form of interesting results.

The empirical results from the various subsamples are quite unanimous. Although the standard error varies from sample to sample, the point estimate of the elasticity of substitution is approximately 0.1 in all samples. It is significantly different from zero when estimated on U.S. and Japanese data from 1973-74, and this result is robust to a wide range of assumptions about electricity prices in Japan. Including observations from 1977-78 and from Norway gives even tighter results.

The results confirm _a priori_ beliefs about limited substitution possibilities for electricity in aluminum reduction. However, the estimated elasticity is large enough to indicate significant potentials for energy conservation. In particular, promises of substantial energy savings from raising prices of hydro power from low historic cost to the high level of current alternative cost are indicated by the results.

Footnotes:

1) This author is not sufficiently familiar with the engineering literature to give a representative list of references. Examples are Grjotheim e.a. (1971) and Light Metals Society (1976).

2) Berndt and Wood (1975,1979), Fuss (1977), Griffin and Gregory (1976), Pindyck (1979), Field and Grebenstein (1977, 1978), and Halvorsen and Ford (1978) are examples of studies of factor demand in manufacturing industries.

3) For an exposition of the putty-clay model, see Johansen (1972).

4) Since the price of electricity changes in finite steps, the function P_E is continuous almost everywhere. This is sufficient for defining its expectation and covariance with output, which is needed in (5).

5) A discussion and survey of the literature on this issue is given by Berndt and Wood (1979).

6) Because of the technical nature of the aluminum smelting process, capacity utilization cannot exceed 100% by very much.

7) This may be justified by assuming that the errors in various parts of a plant are perfectly correlated because they are made by the same management. This is most likely to be true when the whole plant has been constructed or renovated at the same time. It is not always true, though, as can be seen from figures disclosed to the Institute of Industrial Economics by Årdal og Sunndal Verk. At their plant in Årdal, Norway, the four potlines use 15.6, 14.0, 19.4, and 16.9 kwh per kg aluminum respectively, in the electrolytic process.

8) For the case of Japan, the increase is over four years. I adjusted for this by substituting $\frac{4}{5}\,\Theta$ for Θ for the Japanese observation.

9) In Scottsboro, Alabama, Reynolds has both a reduction plant and an alloys plant which are billed separately by TVA. The alloys plant typically takes around 11% of the total power. National aggregates, published by the Aluminum Association (1979), indicate that fabrication takes 9-10% of the electricity used in fabrication and smelting.

10) The large reduction in standard error comes from the large weight assigned to the Japanese observation because it is an average of 13 different plants. See the discussion in the previous section.

11) The weight was determined from the estimated residuals as

$$w' = \frac{\Sigma e_{1i}/n_1}{\Sigma e_{2i}/n_2}^{1/2},$$

where e_{1i} are the residuals of the U.S. '78 observations, e_{2i} all other residuals, and n_1, n_2 the number of observations in the two subsamples. No heteroskedasticity of comparable magnitude was detected for the Japanese or Norwegian observations for 1977/78.

12) A discussion of the likely future location pattern of primary aluminum smelters is given in Mork (1979).

13) Natural gas from interstate pipelines in the U.S. was subject to price controls in this period. However, since shortages occurred, its scarcity value exceeded the controlled price.

14) The Aluminum Association (1979).

References:

The Aluminum Association, Inc., Energy Conservation and the Aluminum Industry, (pamphlet), Washington, D.C. 1979.

Berndt, E.R., M.A. Fuss, and L. Waverman, Dynamic Models of The Industrial Demand for Energy, EPRI EA-580, Research Project 683-1, Interim Report, Palo Alto, Calif., November 1977.

Berndt, E.R. and D.O. Wood, "Technology, Prices and the Derived Demand for Energy", Review of Economics and Statistics, Vol. 75, August 1975, pp 259-268.

Berndt, E.R. and D.O. Wood, "Engineering and Econometric Interpretations of Energy-Capital Complementarity", American Economic Review, Vol. 69, No. 3, June 1979, pp 342-354.

Field, B.C. and C. Grebenstein, "Substituting for Energy in U.S. Manufacturing", processed, June 1977.

Field, B.C. and C. Grebenstein, "Capital-Energy Substitution in U.S. Manufacturing", processed, 1978.

Fuss, M.A., "The Demand for Energy in Canadian Manufacturing: An Example of the Estimation of Production Structures with Many Inputs", Journal of Econometrics, Vol. 5, No. 1, 1977, pp 89-116.

Griffin, J.M. and P.R. Gregory, "Intercountry Translog Model of Energy Substitution Responses", American Economic Review, Vol. 66, No. 5, December 1976, pp 845-857.

Grjotheim, K., C. Krohn, M. Malinovsky, K. Matiasovsky, and J. Thonstad, Aluminum Electrolysis, Aluminium Verlag, Düsseldorf, 1971.

Halvorsen, R. and J. Ford, "Substitution Among Energy, Capital, and Labor Inputs in U.S. Manufacturing", in R.S. Pindyck (ed.), Advances in the Economics of Energy and Resources, Vol. I, JAI Press, Greenwich, Conn., 1978.

Johansen, L., Production Functions, North-Holland, 1972.

Light Metals Society, New Extractive Aluminum Technique, Tokyo, 1976.

Lucas, R., "Optimal Investment Policy and the Flexible Accelerator", International Economic Review, February 1967, pp 78-85.

Mork, K.A., "Elektrisitetspriser og Lokalisering i Primær Aluminiums-smelting -- Et Globalt Perspektiv" ("Electricity Prices and Location in the Primary Aluminum Smelting Industry -- A Global Perspective") Report to the Institute of Industrial Economics, Norway, May 1979.

Pindyck, R.S., The Structure of World Energy Demand, MIT Press, Cambridge, Mass., 1979.

Treadway, A.B., "The Rational Multivariate Flexible Accelerator", *Econometrica*, 39, 1971, pp 845-856.

Data Appendix

Electricity Consumption Data for the U.S.

Electricity consumption data for the Pacific Northwest were obtained from Bonneville Power Administration (BPA). These cover BPA deliveries, replacement (trust) power, and deliveries from other suppliers. The data are supplied per calendar year and broken down by company. Four companies, Alcoa, Reynolds, Kaiser, and Martin Marietta, each have two smelting plants in this region. For the former three, no further breakdown was possible. For Martin Marietta, the deliveries by BPA itself are broken down by plant. Purchases from other suppliers are very small for this company. For 1978, replacement power deliveries were also very small, so that regular BPA deliveries were 98% of total. This justifies splitting electricity consumption for 1978 between the two plants according to their respective shares of regular BPA power. Had the capacities of the two plants been the same in 1974 as in 1978, the same key could have been applied to that year as well; however, the capacity of one of the plants was expanded during this period. The split between the two plants for 1974 was identified by assuming that the percentage change in elcetricity consumption per kilogram aluminum from 1974 to 1978 was the same in the two plants.

For customers of the Tennessee Valley Authority (TVA), electricity consumption per plant per calendar year was supplied by TVA. For Alcoa's plant in Alcoa, Tennessee, the power delivered to Alcoa in return for the power generated at Alcoa's dams was added to the power purchased from TVA.

Alcoa's plant in Warrick, Indiana, apparently gets all of its power from Alcoa Generating Corporation (AGC). Most of this is generated by AGC, and some is purchased from Southern Indiana Gas and Electric. The sales (in kwh) from AGC to industrial customers are published in Statistics of Privately Owned Electric Utilities of the U.S. It is reported to have one industrial customer, obviously Alcoa. Updates for 1978 were obtained from Form 1 filed with the U.S. Federal Energy Regulatory Commision (FERC). Alcoa's plant in Badin, North Carolina, has a similar arrangement with Yadkin, Inc., another subsidiary, and the data was obtained the same way.

Anaconda's plant in Sebree, Kentucky, and National-Southwire in Hawesville, Kentucky, receive power generated by Big Rivers Rural Electric Co-op, Inc. Data for electricity consumption were extracted from Form 12 filed with the FERC and reports on fuel cost adjustment filed with the Commonwealth of Kentucky Energy Regulatory Commission.

Production Data for the U.S.

Plant capacity for 1974 were taken from *Minerals Yearbook*, a publication of the U.S. Bureau of Mines. This gives plant data for all companies except Alcoa. Capacity figures for Alcoa's plants for 1974 and 1978 were obtained directly from Alcoa. Capacity data for 1978 for the remaining plants were provided by the U.S. Bureau of Mines.

Production and capacity data for the Pacific Northwest and the country as a whole, compiled by MC$_2$H-Hill were made available by BPA. For 1974 plant production data were constructed as plant capacity times aggregate capacity utilization in or outside the Pacific Northwest, respectively. The same procedure was used for 1978, but with the following adjustment for plants outside the Pacific Northwest. Two of the plants that are not in the sample were shut down, partly or completely, in 1978. These were Alcoa's plant at Point Comfort, Texas, which was inactive for the whole year because of high prices of natural gas, and Noranda's plant in New Madrid, Missouri, which was closed for about 3 months because of a coal strike. Taking this into account adjusts the capacity utilization rate for the plants in the sample from 92% to 97%.

Information about fabrication activities at the same locations as smelters were obtained from Rocky/Marsh Public Relations, Inc., for the Pacific Northwest and directly from the companies for the rest of the country.

Quantity Data for Norway and Japan

The Norwegian data give electricity consumption, including auxiliary power, per kilogram aluminum by plant. The data were supplied by industry sources to the Institute of Industrial Economics, Bergen, who made them available to me. The information is not dated, but was obtained recently and is assumed to pertain to 1978. The Japanese quantity data are annual national averages of electricity consumption per kilogram aluminum (including auxiliary power), made available to me by The Institute of Energy Economics, Tokyo.

Aluminum Price Data

Metal Statistics, a publication of Metallgesellschaft Aktiengesellschaft, gives aluminum prices for West Germany, U.S., and U.K. Since the last issue gives data only half way into 1978, the data for this year are supplemented by records of announced price increases as given in Mineral Industry Surveys, published monthly by the U.S. Bureau of Mines. Non-U.S.

prices are assumed to have increased by the same percentages as U.S. prices in the second half of 1978. The Japanese price is assumed to equal the U.S. price plus shipping cost. Shipping cost data were supplied by Pacific Westbound Conference, San Francisco. The Norwegian price was taken as the West German price less 1.3% transportation cost.

U.S. Electricity Prices

For the Pacific Northwest, price data can be extracted from the following sources: (i) Annual Reports of BPA, giving average revenue for BPA power; (ii) Statistics of Publicly Owned Utilities in the U.S., giving average revenue for sales to industrial customers for Chelan Public Utility District No. 1, which is a major supplier for Alcoa; (iii) statistics of total outlay for electric power for the aluminum industry in the region, prepared by CH_2M-Hill and made available by BPA; and (iv) statistics from BPA referred to above for total electricity use of the industry in the region. The accounting identity for electricity cost of the industry in the region is

$$C_E = P_B E_B + P_R E_R + P_C E_C + P_O E_O,$$

where C_E is total cost of electricity, $P_B E_B$ is total revenue for BPA deliveries, P_C and E_C are price and quantities for deliveries from Chelan County PUD No. 1, P_R and E_R are price and quantity for replacement power, and P_O and E_O are price and quantity of deliveries from other sources.

Of these, all but P_R and P_O are known. When no replacement power is purchased, P_B is assumed to be the marginal price. This is justified by two facts, (i) P_C is consistently lower than P_B, and (ii) although P_O is higher than P_B, E_O represents only small quantities for auxiliary power such as lighting and is not a regular substitute for Bonneville power. When replacement power is used, P_R is the relevant marginal price. Given reasonable guesses for P_O, the accounting identity can be solved for P_R. P_O is assumed to be 6.75 mills/kwh in 1973 and 12 in 1978. The resulting value of P_R is only marginally sensitive to the choice of P_O because of the low value of E_O. This procedure gives a P_R for 1973 of 5.359 mills/kwh in 1973, which is very sensible compared to Bonneville's price (P_B) of 2.171. For 1978, however, P_R comes out as 65.543, which seems unreasonably high. The explanation seems to lie in the fact that replacement electricity is only 0.5% of total electricity use that year, compared to 15.8% in 1973. This can result in an unreasonable figure either because data inaccuracies are multiplied up or because it may be difficult to buy such relatively small quantities (149 mill. kwh distributed over six months) in the open market at a good price. Thus, based on judgement, it is guessed that $P_R = 25$ is a more reasonable value for replacement power purchased in "normal" quantities. This guess seems reasonable since a similar computation for 1977 gives $P_R = 21.0$ with 6.3% replacement power. The regressions are run with both values of P_R for 1978.

Computation of the expected marginal price requires an estimate of the probability that a company buys replacement power. The information for this estimate is obtained from the statistics of total electricity use by plant from BPA. This source gives monthly data for consumption of replacement power by company 1973-78. A possible measure of the probability is then the average over years and companies of the fraction of the number of months that replacement power has been purchased. This gives a probability estimate of 0.54. This tends to be upward biased, though, because it assumes that replacement power is purchased for the whole month whenever it is used for some fraction of a month. The magnitudes of the monthly figures gives some guidance in this respect, but some judgement was needed in order to arrive at a reasonable figure. I decided to use 0.45 as my estimate.

Electricity data for the rest of the U.S. are much simpler, both conceptually and practically. Declining rate schedules make a slight difference between average and marginal price; however, for customers as large as aluminum smelters, the difference is very small and is ignored. For three of the four TVA customers in the sample, Reynolds, Revere, and Conalco, average revenue per kwh for the calendar year was supplied by TVA. The fourth customer, Alcoa, was a little more difficult. Due to a special contract arrangement, Alcoa pays no energy charge, but the demand charge is computed so that the average cost per kwh is the same as for the other customers if the contracted load demand is fully utilized. Alcoa may reduce its demand with two weeks notice and save 50% of the charge on the reduced load. Thus, Alcoa pays a higher average price than other customers. On the other hand, Alcoa's marginal price is only half of what others pay on the margin as long as Alcoa's demand stays within the limits of its present contract. Alcoa's demand seems to have been within these limits for the years in question. Thus, although large demand increases would cost more on the margin, I assume that Alcoa's marginal price is half of that of TVA's other aluminum customers for the consumption levels in the sample.

Price data for the plants of Anaconda and National Southwire in Kentucky were obtained from the records of the Commonwealth of Kentucky Energy Regulatory Commission. Although these two plants buy power from different electric co-ops, the power for both is actually generated by Big Rivers Rural Electric Co-op. Thus, the two companies effectively buy in the same market . For 1974, the files contained copies of the actual monthly invoices sent to National Southwire. I assumed that the annual average price for 1973 for both companies equaled the price paid by National Southwire in January 1974 less 2.5%. For 1978, industrial rates and monthly fuel charges for Big Rivers Rural Electric Co-op were available, which gave a price estimate for Anaconda. For National Southwire, monthly bills were available for January through September. The annual average was estimated by assuming similar price movements as for Anaconda in the three remaining months.

Alcoa's plant in Indiana gets most of its power from self-generation, but purchases a significant part from Southern Indiana Gas and Electric Co. (SIG & E). Revenue and quantity data for these sales are taken from listing applications to the New York Stock Exchange from SIG & E, with a telephone update for 1978 directly from the utility. Average revenue per kwh for these sales is assumed to be the alternative value of the self-generated power and used as the price of electricity.

Alcoa's plant in North Carolina gets all its power from its subsidiary Yadkin, Inc. According to published figures, Yadkin, Inc. purchases some power in addition to its own generation. Some of the purchases are made from

Duke Power Co., which covers the area. I assume that the industrial rate of this utility is a satisfactory measure of the alternative cost. It may be noted that Alcoa and Duke Power closed a contract for power delivery under these terms in 1976, although no actual sales have taken place to date.

Electricity Prices for Norway and Japan

Price data for Norwegian smelters were extracted from various documents of Stortinget, the Norwegian Parliament (Stortingsproposisjon no. 145, 1961-62, and no. 81 and 165, 1975-76), with updates for 1978 directly from Statskraftverkene, the publicly owned Norwegian power generating company. Two of the Norwegian plants, Årdal og Sunndal Verk's plant in Høyanger, and Det Norske Nitritaktiselskap in Tyssedal, use only self-generated power, and I have not been able to find a reasonable alternative cost measure. I exclude these plants from my sample.

Norsk Hydro's plant at Karmøy gets all its power from Hydro's own network. However, since Hydro's network receives power from Statskraftverkene delivered in Sauda, the contract price of this delivery, plus 10% transmission cost, is taken as the alternative cost of Hydro's own power for this plant. All the remaining plants rely partly or entirely on power from Statskraftverkene. For these, the prices of their most recent contract are taken to be the marginal prices. These may or may not be meaningful. On the one hand, power contracts may effectively have been rationed by the government, which indicates the effective prices are higher. On the other hand, obligations to pay for unused power contracted for, which may have prevailed in older contracts, indicate lower effective prices.

The Institute of Energy Economics, Tokyo, provided national average data for electricity prices to industrial users. It is assumed that aluminum smelters in Japan, like in other countries, pay less than this. Specifically, the average industrial prices are multiplied by the ratio of the price for sales from SIG & E to Alcoa to the U.S. national average of industrial electricity prices. This implies the assumption that Japanese pay a similar fraction of the average industrial price as do aluminum customers of fossil fired utilities in the U.S.

Table A1

Data used for estimation

1973-74

Pacific Northwest, U.S.	PE/PA	E/A	Z	W
Alcoa, Wash.	6.411	19.751	0.5	1.3809
Anaconda, Mont.	6.411	19.9	1.	1.
Martin Marietta, Wash.	6.411	18.195	0.	1.
Martin Marietta, Oreg.	6.411	19.587	0.	1.
Intalco, Wash.	6.411	15.106	0.	1.
Kaiser, Wash.	6.411	20.586	1.	1.28226
Reynolds, Oreg. & Wash.	6.411	18.912	0.5	1.37633
TVA customers, U.S.				
Alcoa, Tenn.	7.585	20.121	1.	1.
Conalco, Tenn.	15.171	15.643	0.	1.
Revere, Ala.	15.171	17.447	1.	1.
Reynolds, Ala.	15.171	18.81	0.	1.
Other U.S.				
Alcoa, Ind.	12.716	19.361	1.	1.
Alcoa, N.C.	15.147	16.26	0.	1.
Anaconda, Ky.	10.223	16.672	0.	1.
National Southwire, Ky.	10.223	19.315	0.	1.
Japan, national avg.	19.026	16.108	0.	3.20479

Table A1, cont'd

1978				
Pacific Northwest, U.S.				
Alcoa, Wash.	10.15	20.978	0.5	1.35645
Anaconda, Mont.	10.15	18.469	1.	1.
Martin Marietta, Wash.	10.15	17.475	0.	1.
Martin Marietta, Oreg.	10.15	18.812	0.	1.
Intalco, Wash.	10.15	16.317	0.	1.
Kaiser, Wash.	10.15	21.344	1.	1.28226
Reynolds, Oreg. & Wash.	10.15	19.813	0.5	1.37633
TVA customers, U.S.				
Alcoa, Tenn.	8.535	20.464	1.	1.
Conalco, Tenn.	17.07	15.299	0.	1.
Revere, Ala.	17.07	19.794	1.	1.
Reynolds, Ala.	17.07	18.862	0.	1.
Other U.S.				
Alcoa, Ind..	22.099	16.645	1.	1.
Alcoa, N.C.	16.438	16.181	0.	1.
Anaconda, Ky.	14.12	16.49	0.	1.
National Southwire, Ky.	14.627	20.294	0.	1.
Japan, national avg.(1977)	31.508	15.728	0.	3.36455

Table A1 cont'd

Norway	PE/PA(73)	PE/PA(78)	E/A(78)
Elkem-Spigerverket, MosJøen	10.387	10.46	18.9
Elkem-Spigerverket, Lista	10.483	6.848	18.7
Norsk Hydro, Karmøy	11.426	7.462	18.2
Sør-Norge Aluminium, Husnes	10.387	6.784	15.9
Aardal og Sunndal Verk, Aardal	9.879	10.65	18.3
Aardal og Sunndal Verk, Sunndalsøra	10.387	10.65	19.1

Z and W are 0 and 1, respectively, for all Norwegian observations.