

IS COAL DESULFURIZATION WORTHWHILE? EVIDENCE FROM THE MARKET*

Short title: Market Evidence on Desulfurized Coal

J. B. Braden, C. D. Kolstad, R. A. Woock, and J. A. Machado**

Contact author:
Prof. John B. Braden
University of Illinois
601 E. John Street
Champaign, IL 61801
USA

j-braden@uiuc.edu
ph. + 217/333-8159
fax +217/244-5639

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** Department of Agricultural and Consumer Economics, Environmental Council, and Office of the Provost, University of Illinois at Urbana-Champaign; Department of Economics and School of Environmental Science and Management, University of California, Santa Barbara; MediaOne Labs, Westminster, CO; and Faculty of Economics, New University of Lisbon, Portugal.

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ABSTRACT

The paper develops a forward-looking way to estimate the economic benefits of research and development on coal desulfurization. The methodology makes use of survey-based techniques pioneered in environmental economics. The empirical results illustrate the difficulty of configuring desulfurized coal to meet the requirements of existing electricity generating plants. The contributions of the paper are in extending survey-based valuation to meet the needs of R&D investors for intelligence about the prospective value of their investments and using robust estimation techniques to reduce the influence of outliers, as well as in estimating the returns to investment in coal desulfurization.

Keywords: Coal, desulfurization, contingent valuation

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I. BACKGROUND

Due to sulfur emission limits imposed by the Clean Air Act, the power industry in the United States has turned to sources of low sulfur coal, and regions with high-sulfur coal reserves have lost billions of dollars in revenues and tens of thousands of jobs previously associated with coal production. In an effort to recapture market position for higher sulfur coals, a great deal of research and development (R&D) has occurred on ways of extracting the sulfur. However, the potential value of successful innovation is difficult to quantify because it is often the case that the desulfurized fuel product has characteristics that make it unlike any good that the market currently offers—including the coals that are naturally low in sulfur. In order to determine whether further R&D is warranted, decision makers in the public and private sectors need to know the likely value of the products that would result from further investment in desulfurization technologies.¹ Based on the results of actual laboratory work, we hypothesize several possible bundles of quality characteristics that could result from successful R&D in this area. We then use a survey method, with utility fuel buyers as respondents, to determine the willingness of electric utilities to pay for these

¹ Fuel switching, allowed in the 1990 Clean Air Act, has become important in the coal and electric power markets. The viability of fuel switching has been enhanced by deregulation of railroads and deregulation of electricity markets. States with abundant high-sulfur coal reserves must solve the sulfur problem if they are to compete effectively as fuel suppliers. However, because desulfurized fuels have not been readily available in the marketplace, market signals are not available to guide investments in desulfurization research and development.

hypothetical new goods. Our results provide insight into the potential value of research on desulfurization.

R&D is generally concerned with innovations that reduce the cost of manufacturing an existing product, improve the quality of an existing product, or develop a new product. When quality improvements or new products are the likely outcomes, one of the key issues in evaluating the viability of investments in R&D is placing a value on the results of innovation. The empirical literature on valuing the results of innovation is relatively sparse (Trajtenberg, 1989; Griliches, 1992). What literature there is looks backward at the welfare and productivity gains that have been achieved by successful innovation, induced by past R&D investment (e.g., Mansfield (1977), Bresnahan (1986), Trajtenberg (1989), and Bresnahan et al (1997)). While retrospection may be useful for measuring the consequences of R&D policy, it is not always useful for planning future R&D investments because the characteristics of future products may lie outside the range of consumers' past experience. This paper seeks to extend the literature on valuing innovation by developing a prospective way of measuring the welfare consequences of successful innovation that lies outside previous experience.

II. BACKGROUND

The problem of estimating demand for a new or changed product has received extensive attention in the marketing literature (e.g., Choffray and Lilien, 1980; Smith, 1986). For example, Tomkovick and Dobie (1995) use hedonic analysis of characteristics to investigate the market for writing instruments. Hedonic methods offer a suitable framework for

estimating the demand (Rosen, 1974; Palmquist, 1991; and Griliches, 1992), but they yield plausible estimates only when the quality combinations that will result from innovation are within the range of market experience. However, coal desulfurization processes can change the composition of coal, producing products with characteristics not seen in the past.

Retrospective analysis of value can not help; forward-looking methods are needed. One such method is contingent valuation, which has been developed primarily in the environmental literature (Carson, 1991; Carson *et al.*, 1994; Freeman, 1993; Diamond and Hausman, 1994; Hanemann, 1994; Portney, 1994), for studying new product demand. However, this approach confronts potential biases in responses as well as the aforementioned problem in translating expressed intentions into actual behavior (Carson, 1991; Hanemann, 1994; Diamond and Hausman, 1994).

With regard to coal choices by electric utilities, most previous studies are concerned with engineering issues (e.g., Barrett *et al.*, 1981; Buden *et al.*, 1979; Curlett, *et al.*, 1983; Higazy and Kenning, 1983; Honea *et al.*, 1981; and Phillips and Cole, 1980). There has been little work on the effects of coal quality on generating costs, although studies of fuel switching (e.g., Bopp and Costello, 1990; Ellerman, 1996; Joskow and Mishkin, 1997; USDOE/EIA, 1986; and EPRI, 1986) address similar questions.

Coal is a familiar product to most electric utilities and there is much available data on utility coal purchases (e.g., USDOE/EIA, 1986). These transactions data include some major quality attributes of the coal involved: sulfur, ash, moisture, and thermal content as well as origin and destination. However, most technologies that have been developed to reduce sulfur levels in coal also tend to affect attributes that are not reflected in the coal transactions

data: volatility, grindability, particle size distribution, and ash chemistry.² Some of the key attribute changes are not recorded in market data, so there is no basis from which to estimate the importance of alterations caused in the course of desulfurization. Data concerning those attributes must be elicited in order to develop an appropriate demand assessment. In the following sections, we specify a model of multi-attribute product quality choice and apply the model to estimate the demand for desulfurized coal products using contingent valuation.

III. ATTRIBUTE-BASED MODEL OF FUEL CHOICE

There are two important components to estimating input demand. First, the proper microeconomic framework must be developed to allow measurement of demand. Second, a survey instrument must be constructed to collect needed data that cannot be obtained from markets. The framework is developed in this section and the empirical methodologies outlined are in the next. The discussion is framed for the particular intermediate addressed in our subsequent empirical analysis, desulfurized coal characterized by thermal content, sulfur content and volatility level.

The short-run demand for desulfurized coal depends on the production technology employed by individual power plants and electric utilities. In order to assess that demand, we make use of the duality between the technology of a firm and its cost of production. The technology for electricity generation from coal can be represented by the short run production function:

² There are four broad alternatives for reducing the sulfur in a utility's boiler charge: low and high sulfur coal blending; physical cleaning of the nonorganic fraction of the sulfur in coal; chemical cleaning of the organic fraction; and hydrolysis of the sulfur-containing volatile matter, creating char.

$$y = Y(Q, \mathbf{Z}, \alpha, K, L) \quad (1)$$

where:

y = net megawatt hours (Mwh) of electricity production generated with coal,

Q = thermal content (MMBtu) of coal used,

\mathbf{Z} = a vector of coal quality characteristics such as sulfur content, volatility, grindability, ash fusion temperature, etc., measured per MMBtu,

α = characteristics of the plant,

and where capital (K) and labor (L) are assumed fixed and unchanging in the short-run.

Production of electricity varies with both the quantity and quality of the coal input only.

Fixed technologies restrict the degree to which attributes may be varied or inputs of different quality may be mixed.

Prior to 1990, the Clean Air Act required power plants either to install flue gas scrubbers, which make sulfur content irrelevant, or to abide by fuel quality restriction in their operating permits. One way to represent these regulatory constraint on fuel choice is to separate out the qualities of coals actually purchased from those of the coals which are available. We will call the actual purchases the "reference coal" and the alternatives the "desulfurized coal." Subject to technology restrictions, the utility can elect to mix the two coals, or consume only one or the other. With this change, we can rewrite the production function as:

$$y = Y(Q_R, \mathbf{Z}_R, Q_D, \mathbf{Z}_D, K, L) \quad (2)$$

where R,D index the reference and desulfurized coals respectively. We can completely describe the production technology by using the dual cost function:

$$C = C(y, w_R, w_D, Z_R, Z_D, K, L) \quad (3)$$

where:

$y =$ output (Mwh);

$w_i =$ input prices for coal ($\text{\$/MMBtu}$), $i = R, D$;

$Z_i =$ coal quality characteristics, $i = R, D$;

$c =$ total fuel cost (reference plus desulfurized).

The first three arguments are standard--output and own- and substitute prices. Costs should increase in input prices and output quantities. The fourth and fifth arguments and unconventional in most input demand studies--quality attributes of the input alternatives, but they are important in coal markets. Premiums and penalties are commonly stipulated for variations in coal quality that affect (positively or negatively) the electricity generation process. In general higher quality coals are worth more because they cut down operation and maintenance costs. The reduction in generating costs may more than offset higher delivered prices for the better coal. Hence, the cost of generating electricity is a function of the quality of the coal, as well as the price of the commodity.

We adopt a Generalized Leontief cost function as a flexible dual representation of the technology with $i=1, \dots, I$ inputs, and $j=1, \dots, J$ quality characteristics (Diewert and Wales, 1987). Furthermore, we suppress the K and L terms by assuming in our constant returns implementation that the capital-output and labor-output ratios are fixed over the sample. The coal quality characteristics of particular interest in our empirical application are the

volatile matter content (V) in lbs/MMBtu and sulfur content (S) in lbs/MMBtu of the two coal products. We thus have four coal characteristics: z_{R_S} , z_{R_V} , z_{D_S} , and z_{D_V} .

Writing the cost function in terms of the specific coal alternatives, as a unit cost function to allow for the possibility of heteroskedasticity in plant size or output, assuming linear homogeneity, and assuming a normalization of input quantities as suggested by Diewert and Wales' (1987) yields the following specification:³

$$C/y = c(w_R, w_D, z_{R_S}, z_{R_V}, z_{D_S}, z_{D_V})$$

$$= \sum_i \sum_j \beta_{ij} w_i^{1/2} w_j^{1/2} + \sum_i \sum_j \delta_{ij} w_i z_j + \sum_k \sum_j \xi_{kj} z_k z_j \sum_i \bar{x}_i w_i$$
(4)

This cost function is expected to be concave in input prices and will be so globally if $\beta_{ij} \geq 0$, $i \neq j$. Applying Shepard's Lemma gives the derived conditional unit factor demand equation for the desulfurized fuel product:

$$q_D = Q_D/y = \beta_{DD} + \beta_{DR} (w_R/w_D)^{1/2} + \sum_j \delta_{Dj} z_j + \bar{Q}_D \sum_k \sum_j \xi_{kj} z_k z_j$$
(5)

where q_D is MMBtu/Mwh of the desulfurized fuel, and \bar{Q}_D equals the sample average quantity of thermal content (MMBtu's) replaced by desulfurized coal, in accordance with the normalization. The addition of a stochastic error term $e_D \sim N(0, \sigma^2)$ to equation (4) or (5) results in an estimable model that is linear in the parameters.⁴

³ The details of the derivations in this section are available from the authors.

⁴ In equation (5), there is the possibility of zero quantity choices. This would make (5) nonlinear in the parameters and necessitate use of limited dependent variable methods.

IV. EMPIRICAL METHODOLOGY

A key attribute of coal, its volatility, is not routinely recorded in transaction data.⁵ This attribute is significantly affected by some of the most promising desulfurization technologies, so we must elicit data about preferences for this attribute in order to estimate the overall economic value of those technologies.⁶

The typical market experience of electric utility fuel buyers is to determine what amount(s) and type(s) of coal to buy and consume at posted prices. Thus, if the survey methodology is to emulate the real purchasing process, as it should, it must collect "quantity bids" instead of "price bids." The survey must ask how much are utilities *willing to buy* at hypothetical prices, not how much are they willing to pay for desulfurized coal. By varying the quoted prices, as well as coal characteristics, across the survey sample, the willingness-to-buy format will generate all the information needed to estimate demand functions for coal attributes.

⁵The importance of volatility can be appreciated by considering the difficulty in starting charcoal with a match without first increasing the volatility by adding lighter fluid.

⁶ Market data for electric utility coal purchases have been collected by the USDOE since the early 1970's (e.g., USDOE, 1986). These data include the source and destination of the coal, and its thermal, sulfur, and ash content. The data set does not include volatile matter content. Elsewhere, we report ash and sulfur values estimated from the USDOE data (Kolstad *et al.*, 1987).

A unique survey conducted in 1987 provides the basis for our analysis.⁷ It employs a "payment card" format (see Carson, 1991) to elicit bids for a hypothetical synthetic coal product. The payment card format starts by specifying a "price change" (here an increment with respect to the price(s) paid for currently used fuel) and then asks the respondent to choose an amount that best describes his buying intention. If the respondent chooses not to buy at the quoted price, he or she is given the option to quote a price at which they would be willing to buy an amount equal to five percent of their most recent year's fuel purchases. Thus, for some respondents, there is the prospect of two observations on the demand curve: one with the quoted price and zero quantity and the other with a selected price and a particular quantity geared to the size of the facility. For others, there will be only one observation: the stated price and a resulting nonzero quantity. Even with the prospect of multiple observations, however, a small population of buyers makes a discrete choice random utility model undesirable; there are fewer than 100 different coal buyers in the states within market range of Illinois, the focal point of the desulfurization technologies considered here.

Product Specification

A key element of the contingent valuation approach involves specifying the target commodity. Because there are few "real" desulfurized fuels on the market, we took as

⁷Appendix A to this paper contains the survey instrument used. Appendix B presents the raw data resulting from the survey. Appendix C defines the different alternative fuels used in the survey. And Appendix D presents the population and sample. All four appendices are available upon request from the authors. The material may also be found in Kolstad *et al* (1987). Although the data are quite dated, the methods are the message of this paper and those are unaffected by the fact that the data are not recent.

references laboratory analyses of two desulfurized fuels that have been produced in laboratories of Illinois' State Geological Survey, one a char and one a froth-flotation product. We then generated hypothetical candidate commodities by perturbing some of the attributes, staying within the range of quality levels indicated by the laboratory analyses as well as advice received from coal chemists. The coal specifications were selected to span this range of attribute quality. Specifically, three sulfur content levels (0.45%, 0.95% and 1.78%), three volatility levels (15.12%, 25.14% and 35.26%), and two ash fusion temperatures were identified. All possible combinations of these levels yields 18 different fuel quality bundles.

The ash fusion temperatures distinguish between two fundamentally different boiler types. "Wet-bottom" furnaces must melt the ash, which requires a low ash fusion temperature (2400°F and below). "Dry-bottom" furnaces keep ash in a solid state, for which a higher fusion temperature is needed. Because of this fundamental difference in boiler technologies, the nine products with high ash fusion temperature were restricted to dry-bottom generating units and those with low fusion temperature to wet-bottom units. The nature of the generating units is public information.⁸

Other important attributes of the desulfurized fuel were held constant over the sample: moisture content (6.57% as received), chlorine content (0.10% moisture and ash free), equilibrium moisture (4.5%) and Hardgrove Grindability Index (48 at 4.5% moisture).

⁸All of the fuel specifications appear in Appendix C, available from the authors upon request. The specifications were presented to respondents in a way resembling the laboratory test reports utilized by many electric utilities to monitor coal quality. This helped to assure familiarity with the context of the survey.

Finally, using the data in the proximate analysis and a "Dulong-type equation" (Combustion Engineering, 1981, pp. 2-12), the thermal content (Btu/lb) levels were calculated.

Starting Points

A "payment card" question to elicit the "quantity bid" must specify: 1) a "reasonable" price for the product being offered--i.e., a price at which the question "how much are you willing to buy" is plausible to respondents; and 2) an appropriate array of response options. On the latter score, the utilities are asked to choose the percentage of their 1986 coal usage that they would be willing to replace with the offered product. The result is multiplied by annual coal consumption per boiler (obtained from the USDOE) to determine actual quantity. This approach tailors the question to the individual unit, admits the realistic option of mixing fuels, and avoids the need to scale the survey instrument to small and large units.

Concerning the starting price, two major issues are involved: 1) the prices should reflect the qualities of the fuels, particularly its sulfur content and volatility; and, 2) some provision must be made to avoid non-informative zero purchases that would be induced by starting at too high a price. Furthermore, since the valuation of sulfur and volatility is likely to differ from utility to utility,⁹ the offer prices must be "personalized," i.e., set within the range of each utility's likely valuation.

⁹Much of the variation will be due to the applicable sulfur regulation, embodied in the sulfur content of the reference fuel.

The utility-specific offer prices were generated in four steps: 1) using data from 1986 on the coal purchases for plant i ,¹⁰ partial elasticities of the price paid with respect to the sulfur content and Btu (as a proxy for volatility) were computed (denoted ϵ_{si} and ϵ_{bi} respectively); 2) using these same time-series, averages of the price, sulfur and Btu (\bar{p}_i , \bar{s}_i , and \bar{b}_i) were calculated; 3) with this information and knowledge of the sulfur and Btu contents of the hypothetical fuel being offered to plant i (s_i , b_i), an estimate of the premium or discount (relative to \bar{p}_i) at which the clean fuel will be offered is constructed using the following relationship:

$$\frac{P_i}{\bar{P}_i} = 1 + \epsilon_{si} \frac{\bar{S}_i - S_i}{\bar{S}_i} + \epsilon_{bi} \frac{\bar{b}_i - b_i}{\bar{b}_i}, \quad (6)$$

4) this premium or discount multiplied by a quantity weighted average of past prices (the "reference price") gave the offer price of the fuel. The last step is presented to survey respondents explicitly.

Bidding Process

As was noted above, the fuel buyers were quoted an offer price (cents/million metric BTU) calibrated to their recent experience and asked to respond with a quantity they would purchase at that price. The quantity was actually expressed as a percentage of their coal usage in the previous year, and the respondent was able to answer by marking one point on a continuous line labeled from zero percent to 100 percent. Those who marked zero percent

¹⁰These data are collected on Federal Energy Regulatory Commission form 423.

were asked to quote a price at which they would be willing to substitute the offered coal for five percent of the fuel they would otherwise purchase.

Bias Precautions

Contingent valuation methods confront the potential for biased responses, although the results of numerous studies indicate that careful design can minimize systematic bias (Carson, 1991; Hanemann, 1994). Several measures were taken to prevent bias in the responses to the coal buying survey. First, the survey process was not anonymous. Although confidentiality was promised for reporting purposes, the names and contact information for respondents was collected. Thus, respondents who gave implausible answers could be personally identified and contacted. Second, based on data provided in reports to the Department of Energy, detailed information on the operations of the respondent's generating station was replicated in the survey. This served as a reminder of the fuel quality in use at the plant and ensured that the respondents had the same information as the researchers. One element missing from the public data was the volatile matter content of purchased coal. Respondents were asked to provide this information. Third, the offered fuel was fully characterized using the exact type of laboratory report routinely used by power buyers to verify the quality of their purchases. Fourth, the respondents were asked to rate on a Likert-type scale how various aspects of the coal specification influence their evaluation of the quality of the product. As discussed in more detail below, analysis of the responses did not identify any that consistently exerted strongly negative or positive influences. Finally, the respondents were invited to comment openly about the survey.

Despite these safeguards, it must be recognized that coal quality is carefully selected and monitored at power stations. Large sums are at risk since generating units are finely-tuned to the quality of the fuel. Thus, coal buyers are likely to be quite cautious about unfamiliar or “different” fuel attributes. The respondents were explicitly asked to “be imaginative and flexible” in their responses and to envision that the product would be supplied by a reliable and reputable supplier and delivered and handled according to their normal procedures, that their customary premia or penalties for quality variations away from the quoted levels would be honored, that no penalties would be incurred for reducing purchases from other suppliers, and that air quality regulations would remain at then-current levels. Although the buyers did not express any systematic reservations about these conditions in their evaluation of the survey instrument, habitual caution may have led to understatement of likely long-run responses to the emergence of an alternative type of coal.

V. RESULTS

Data

Seventy-seven survey forms were sent in mid-1987 to coal purchasing officials representing 55 companies in the 13 states where Illinois coal was shipped in 1986. Each form related to a single generating station, some of which include multiple generating units.¹¹ Sixty-two forms were returned, some after reminder letters or calls, for a response rate

¹¹Output in Mwh for each plant are taken from Table 13 of the USDOE/EIA’s “Electric Power Quarterly.”

slightly over 80%.¹² Summaries of the attributes of the reference coals purchased by the respondents, attributes and prices of the desulfurized fuels offered to them, and their responses to the "percentage replacement" question appear in Table 1. As indicated in the bottom portion of Table 1, about 66% of the sample received a product description with sulfur levels below their current fuel mixes, 61% received descriptions with volatile matter levels below their current levels, and the offered fuels had very favorable thermal qualities.

Prior to applying the framework developed above, we investigated two aspects of the survey responses. One was the distinction between low- and high-fusion temperature furnaces. Using a somewhat different model, the hypothesis of different coal purchasing behavior between these two groups was clearly rejected (Kolstad *et al.*, 1987). This reinforces our approach of tailoring the ash specifications in the survey to the known operating characteristics of individual generating stations, then pooling all observations in a single estimation process.

The second pretest concerned the adequacy of our survey design. A final question in the survey inquired about the credibility of various aspects of the survey instrument and about uncontrolled factors that might have influenced the responses. Analysis of the responses indicated no consistent difficulties with the coal attributes that were used nor with the market context as it was specified in the instrument.

¹²Appendix D indicates the extent of the sample and nonrespondents. Appendix B summarizes the raw survey results. Both appendices are available from the authors upon request.

Estimation

Most of the firms in our sample fall within bounds established by Christensen and Green (1976) for no significant economies or diseconomies of scale. Thus, we imposed the constant-returns restriction on the parameters γ_i , λ_{kj} , and ξ_y in equation (4). We first estimated equation (6) using ordinary least squares procedures, then took the derivative of (6) with respect to w_D to get an estimated factor demand equation.¹³ The results for the factor demand equation are presented in the first column of Table 2.

Some common regression diagnostics identified three problems with the unrestricted OLS model. First, following Belsley (1982), we found severe multicollinearity in the data, particularly among the quality characteristic interaction terms (ξ_i 's). Second, the Jarque-Bera Lagrange multiplier test indicated a non-normal error structure. Third, following the procedures set out in Belsley, Kuh and Welsch (1980) and Rousseeuw and Leroy (1987), we found several influential observations and leverage points--both signs of outliers in the data. This was a major reason for pursuing robust estimation techniques.

The first step taken to address these problems was to reduce the dimension of the design by eliminating the quality characteristic interaction terms (ξ_i 's). This is justifiable on two counts: the likelihood ratio tests do not reject $\xi = 0$ and multicollinearity diagnostics improve with these terms removed. This increases the ratio of observations to parameters to almost

¹³We also estimated equation (7) directly using Tobit procedures to account for zero responses on desulfurized fuel quantities. In doing so, we encountered a statistically insignificant estimate of coefficient β_{DR} with a perverse sign. That coefficient value produced nonsensical results for subsequent elasticity estimates and, hence, the directly estimated input demand function was discarded in favor of the parent cost function estimates.

10. Note from Table 2 that the adjusted R^2 does not change very much when these terms are dropped, nor do the parameter values, at least those that are significant.

The second step was to use robust estimator methods on the restricted design. There is a behavioral justification for these methods that deemphasize outliers. First, the hypothetical nature of questionnaires will produce more outlying responses than one would expect in a market situation where real resources are expended. Second, the design in this survey contains elements over which we had complete control (specification of the desulfurized fuel characteristics) and elements over which we had no control (specification of the reference fuel characteristics). This increases the likelihood of outlying responses (Moesteller and Tukey, 1977).

We applied two different robust (L-) estimators: Trimmed Least Squares (TLS) (Ruppert and Carroll, 1980; Welsh, 1987) and Least Absolute Errors (LAE) (Greene, 2000; Judge *et al.*, 1985; Rousseeuw and Leroy, 1987). Inference based on asymptotic test statistics is well defined in both cases, but there is a contrast in the treatment of outliers in the two methods. The TLS estimator "throws away" the outlying observations. The LAE estimator "down-weights" the influence of outlying observations, without purging them. Thus, these estimators provide different degrees of deemphasis of outliers.

Results for the restricted models are also given in Table 2 and arranged for comparison of the estimators. Note that most of the coefficients are similar among the several estimators. Signs are consistent across the estimators excepts for the estimate for δ_{DDV} , the coefficient on volatile matter content of the desulfurized fuel. The most striking result is that the use of robust estimators greatly increases the significance of coefficient estimates. Nearly all of the

coefficients for both the TLS and LAE estimators are significant, whereas very few are for the OLS estimate. This suggests that outliers are significant in this type of data and are best de-emphasized.

An alternate way of viewing these results is through the elasticity of demand for desulfurized fuel, both with respect to the price of desulfurized fuel but also with respect to the quality characteristics of the desulfurized fuel and the reference fuel. Table 3 shows these elasticities for the four models. Focusing on the two robust estimators (TLS and LAE), we note that the elasticities are generally significant at the 90% level. The own price elasticity has a perverse sign for the TLS estimator. Furthermore, the TLS estimates of two other elasticities are positive in contrast to the three other models where those elasticities are negative. This may be because of the information that is discarded in trimming.

The price elasticity of demand for desulfurized product with respect to the sulfur content of the desulfurized product is negative as expected for both robust estimators: higher sulfur reduces demand. It is unclear why the elasticity with respect to reference fuel sulfur content is also negative; this would be expected to be positive.

There is no a priori reason why the elasticity with respect to volatility should be positive or negative. In fact, we would expect that for low volatility levels, added volatility is desirable whereas for higher levels it may be less desirable. The results are mixed. For the TLS estimator, increasing volatility of the desulfurized fuel increases consumption of the desulfurized fuel. The opposite is true for the other estimators. On the other hand, increasing volatility of the reference fuel also increases consumption of the desulfurized product in the case of the TLS estimator.

Policy Analysis

For purposes of estimating the value of investment in a new desulfurized coal product, the potential revenue stream to be realized is of chief interest. Our valuation methodology provides insight. Using the TLS coefficient estimates and assuming mean values for product attributes, reference coal attributes, and prices, and assuming no price discrimination, our results imply that none of the desulfurized coal would be purchased. (Placing these mean values into equation (7) produces a negative number for quantity of heat input from the desulfurized fuel per unit of electricity output.) A discount of 32 percent from the mean price of the reference coal would be required to achieve positive demand. This result is clearly not conclusive given the difficulties of the data set, and it could be moderated by new products that retain more qualities of the natural coal, but it does raise doubt about the social value of investment in desulfurization technology.

VI. CONCLUSIONS

This paper has addressed the viability of desulfurization as a means of shoring up the position of high-sulfur coals in energy markets. The analysis is based on estimating the demand for new products arising from research and development when product attributes range outside past experience in the marketplace. The methodology involves decomposing the product into attribute vectors and using survey-based techniques to assess new combinations of the underlying attributes. The problem of hypothetical bias in contingent valuation is ameliorated by the fact that respondents are very familiar with the decision making context and the ultimate usefulness of the goods presented to them and much better

able to evaluate willingness-to-pay than in the case of final consumers. Perhaps because the decision context is so well defined, however, the problem of outliers is a significant problem in our case study. The outliers reduce the efficiency of ordinary least squares estimates of demand. Adoption of robust estimation methods greatly improves efficiency.

We used four estimates of the derived demand function to provide illustrative demand elasticities for desulfurized fuel. The results suggest that the demand for the desulfurized product is negatively affected by both own and reference sulfur content. The result for reference sulfur is surprising, implying that it is difficult to substitute for high sulfur coal, perhaps because of boiler limitations or the presence of scrubbers. The results for volatility are more mixed between estimators. Here again, restrictive boiler configurations could prevent easy fuel substitution.

The policy implications of our results are important. Given conditions in the late 1980s, it was clear that the desulfurized coal products under development at that time could not compete in the marketplace, at least in the short term. If anything, subsequent long-run changes in the coal market toward lower-BTU, lower-sulfur western coals have further eroded the competitiveness of products that require buyers to accept difficult attributes, such as low volatility, in order to receive higher BTU content. This suggests that research and development of synthetic fuels needs to address more carefully the attributes customers desire and the price premium customers are willing to pay before expending large sums on products that may be viewed as inferior and certainly not worth a significant price premium.

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Table 1. Summary Statistics for Sample

	Mean	St. Dev.	Min.	Max.
Reference Coal Attributes:				
Price (¢/MMBtu)	163.47	46.09	88.80	357.85
Sulfur (lbs/MMBtu)	1.55	1.00	0.23	4.73
Volatility (lbs/MMBtu) ^a	33.52	6.52	25.20	53.13
Avg. Thermal Content (Btu/lb)	11,072	1,391	8,282	13,238
Desulfurized Coal Attributes:				
Price (¢/MMBtu) ^b	131.89	57.90	18.06	281.32
Sulfur (lbs/MMBtu)	0.79	0.41	0.31	1.32
Volatility (lbs/MMBtu)	17.84	6.02	10.27	25.66
Thermal Content (Btu/lb)	14,022	500	13,532	14,952
Desulfurized Coal				
Purchase (% of 1986 tonnage)	10.18	21.28	0	100
Purchases > 0 (No.)	30.00	-	-	-
SD ^c (% of offers)	66.13	-	-	-
VD ^d (% of offers)	61.29	-	-	-

n = 62

^a Computed over the 47 answers to question 6 of the survey (only "dry basis" answers were considered).

^b Price was either specified in the survey or quoted by respondent as the maximum price which would lead to a purchase of 5% of the total coal purchased in 1986.

^c SD = 1 if sulfur treatment \leq reference sulfur, 0 otherwise. Mean (SD) roughly indicates the proportion of cases for which the offered fuel was compliance.

^d VD = 1 if volatility treatment \leq min volatility specification stated by respondents, 0 otherwise. Mean VD indicates the proportion of plants for which the technological constraint on volatility level was binding.

Table 2. Estimated Coefficients of Demand Function for Desulfurized Fuel, Unrestricted and Restricted Models^a

Parameter	Unrestricted OLS	Restricted Models		
		OLS	TLS ($\alpha=0.01$)	LAE
β_{DD}	18.52** (2.76)	12.0** (2.25)	12.66** (4.83)	10.93** (3.24)
β_{DR}	-8.87 (-0.92)	-2.14 (-0.26)	-19.88** (-4.87)	2.34 (0.56)
δ_{DDS}	0.937 (0.38)	-1.15 (-0.53)	-3.13** (-2.91)	-2.19* (-1.60)
δ_{DDV}	-0.186 (-1.10)	-0.06 (-0.51)	0.195** (3.44)	-0.11* (-1.48)
δ_{DRS}	-1.95** (-1.68)	-1.18* (-1.28)	-1.31** (-2.89)	-0.87* (-1.60)
δ_{DRV}	-0.211* (-1.28)	-0.17* (-1.36)	-0.010* (-1.61)	-0.20** (-2.53)
ξ_{DSDS}	8.21E-9 (0.13)	-	-	-
ξ_{DSDV}	-2.56E-9 (-1.07)	-	-	-
ξ_{DSRS}	4.75E-9 (0.29)	-	-	-
ξ_{DSRV}	3.96E-9* (1.32)	-	-	-
ξ_{DVRS}	7.00E-10 (0.59)	-	-	-
ξ_{DVRV}	3.53E-11 (0.18)	-	-	-
ξ_{DVDV}	3.59E-10** (1.67)	-	-	-
ξ_{RVRV}	-2.07E-10 (-1.16)	-	-	-
ξ_{RVRS}	2.82E-9** (1.85)	-	-	-
ξ_{RSRS}	3.18E-9 (0.53)	-	-	-
Adj R ²	0.791	0.780	0.595	0.765

^a Estimation is of eqn. 6, the unit cost function; estimated parameters are only reported for coefficients that appear in eqn. 7, the unit factor demand function. LAE \equiv least absolute error; TLS \equiv trimmed least squares with trimming proportion $\alpha = 0.01$. Sample size is 62; 21 observations are eliminated with TLS. t-statistics are in parentheses; for OLS, standard errors computed using White's (1987) correction for heteroskedasticity. ** indicates significance at 1%; * at 5%. In the absence of a constant term in the estimating equation, the summary statistics may be unreliable. Furthermore, adjusted R² is not well defined for the TLS and LAE estimators.

Table 3. Elasticity of Demand for Desulfurized Fuel with Respect to Price and Coal Quality

Attribute	Estimator			
	Unrestricted OLS	Restricted OLS	TLS	LAE
w_D	4.25* (1.40)	1.02 (0.37)	9.52** (4.87)	-1.12 (-0.56)
z_{DS}	0.633 (0.67)	-0.775 (-0.83)	-2.11** (-2.91)	-1.48* (-1.60)
z_{DV}	-2.85** (-1.81)	-0.907 (-0.95)	3.00** (3.44)	-1.71* (-1.48)
z_{RS}	-2.60** (-2.63)	-1.58** (-2.33)	-1.75** (-2.89)	-1.17 (-1.60)
z_{RV}	-6.08** (-1.84)	-4.94** (-2.09)	2.87* (1.61)	-5.80** (-2.53)

^a See footnote on Table 2. t-statistics are in parentheses; * indicates significance at 90% level, ** indicates significance at 95% level.