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ENVIRONMENTAL CONCERNS AND RESOURCE SCARCITY: THE CASE OF COAL

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ABSTRACT

Traditional measures of resource scarcity have primarily been concerned with the extraction and use of a single natural resource. The relationship between the concurrent use of environmental and extractible resources has attracted little attention. In this article, a conceptual measure of resource scarcity under conditions of simultaneous joint use is developed. This measure includes previously derived indices as special cases. An empirical measure of scarcity under conditions of joint use is derived for coal and air using a translog reproducible cost function. Results suggest that existing environmental regulations have effectively increased the scarcity rent of coal in-use.

I. INTRODUCTION

An increasing awareness of the impacts of environmental pollution has elicited numerous normative and positive economic models. Existing literature has primarily been concerned with identifying optimal amounts of pollution under varying assumptions [1-3]. The relationship between the concurrent use of environmental and extractible resources, however, has attracted only minimal attention except for the questions raised by Krutilla and Fisher [4], Fisher [5], and Smith [6].

In this article, a conceptual measure of natural resource scarcity is developed from a deterministic optimal control model of joint extractible and environmental

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use. The stock or assimilative capacity of the environmental resource is viewed as a repository for the wastes discharged from the extraction and use of another natural resource. The resulting shadow price or scarcity index thus derived is different from previous analyses in that joint use is explicitly accounted for. An empirical measure of joint resource scarcity for the simultaneous use of coal and air in the generation of electricity is estimated using a translog reproducible cost function. These results are then compared to those corresponding to traditional measures of scarcity.

II. COMMON MEASURES OF RESOURCE SCARCITY

Fisher [7] and Tietinberg [8] identify five measures of resource scarcity, three of which are economic, including 1) market price, 2) unit extraction costs and 3) shadow price or scarcity rent. Each measure has associated with it certain advantages and disadvantages.

For instance, market prices reflect scarcity only for those goods traded in perfectly competitive markets, with all the conditions implied therein. Unit extraction cost may or may not reflect scarcity depending on changes in technology or the resource stock. Unit extraction costs are useful in describing past events but may not reflect future conditions. Scarcity (in situ) rent or shadow price may be one of the best measures of scarcity but data limitations have precluded its use until a relatively recent innovation by Halvorsen and Smith in which they derived an empirical scarcity measure for a vertically integrated natural resource industry through the use of duality theory [9].

III. AN OPTIMAL CONTROL MODEL OF JOINT RESOURCE USE

The extraction and processing of many natural resources require the simultaneous use of at least one other input–the environment. In order to capture the total use of the environment, assume that the same firm (industry) performs both the extraction and processing activities in the production of a final good or services. From a firm's perspective, the net surplus from the sale of its final good or service over an infinite time horizon is maximized. The net surplus is derived at each instant of time by subtracting the costs associated with extraction and processing from the total revenue generated from the sale of the finished product, or

$$V = P_y Y[N(X, E, K^e, T), E, K^p, T] - C[N(X, E, K^e), X, E, W, T] - WK^p \quad (1)$$

where P_y = price of final output exogenous to the firm; Y = final output production function; N = natural resource extraction function; X = stock of the extractible resource; E = stock of environmental resource; K^e = composite measure of capital and labor for extraction; K^P = composite measure of capital and labor for processing; T = technology; W = cost of capital labor inputs; and C = cost function of extractible natural resource.

Over the relevant range of values, the extraction cost is assumed smooth, continuous, and twice differentiable; inversely related to the level of resource stock (i.e., $C_X, C_{XX}, C_E, C_{EE} < 0$); but directly related to the extraction rate (i.e., $C_N > 0$; $C_{NN} < 0$). The final output production function $Y(\cdot)$, is also assumed smooth, continuous, twice differentiable and weakly separable in the extracted resource, $N(\cdot)$,[1] and other inputs. In addition, changes in final output levels are Y_N, Y_E, Y_{EE}, Y_{KP} and $Y_T > 0$ with Y_{NN}, Y_{KPKP} and $Y_{TT} < 0$. The competitive equilibrium is given by:

$$\text{Max } V = \int_{t=0}^{\infty} e^{-rt} [P_y Y(N\{X, E, K^e, T\}, E, K^P, T) - WK^P - C(N(\cdot), X, E, W, T)]\, dt \quad (2)$$

subject to

$$\frac{dX}{dt} = f(X) - N(X, E, K^e, T) \quad (3)$$

and

$$\frac{dE}{dt} = \gamma E - N(X, E, K^e, T) \quad (4)$$

where $X(0) = X_0 \geqq 0$; $E(0) = E_0 > 0$, $N(t) \neq 0$ for any time interval [a, b], $\alpha > 0$, $\gamma \leqslant 1$ and f(X) = natural resource growth function.[2] Since the final output price, P_y, is given to the firm, profit or net surplus is maximized by controlling the kevel of K^e in $N(\cdot)$ and/or K^P in $Y(\cdot)$. The current value Hamiltonian for this problem is:

$$\begin{aligned} H = {} & P_y Y[N(X, E, K^e, T), E, K^P, T] - WK^P - C(N(\cdot), X, E, W, T) \\ & + \mu_1 [f(x) - N(X, E, K^e, T)] + \mu_2 [\gamma E - N(X, E, K^e, T)] \end{aligned} \quad (5)$$

In the formulation, μ_1 and μ_2 represent the current value shadow prices associated with the level of stocks of the extractible and environmental resources, respectively. The shadow prices, or scarcity rent, can be interpreted as the marginal loss of current profit due to future extraction and use of these resources.

The necessary first-order conditions are:

$$\mu_1 = P_y Y_N - \alpha C_N - \mu_2 \quad (6)$$

$$P_y Y_{KP} = W \quad (7)$$

[1] This assumption is based on Theorem 3.4 and its corollary 3.4.1 as given by Blackorby, et al. [10, pp. 70–78].

[2] For an exhaustible, in contrast to renewable, resource, f(X) = 0.

$$\frac{d\mu_1}{dt} = (r - f'(X)]\mu_1 + \alpha C_X \tag{8}$$

$$\frac{d\mu_2}{dt} = (r - \gamma)\mu_2 - Y_E + \alpha C_E \tag{9}$$

Equation (6) describes the fundamental efficiency condition in a competitive market of joint resource use. At any point along a firm's optimal extraction and use path of both resources, the marginal loss in profit (μ_1) must equal the difference between the value of the marginal product of the extractible resource, the marginal cost of extraction, and the shadow price of the environmental resource, μ_2. Rearranging Eq. (6) yields

$$\mu = \mu_1 + \mu_2 = P_y Y_N - \alpha C_N \tag{10}$$

In traditional analysis of optimal resource extraction and use, μ_2 does not appear because the environmental resource and its use has never explicitly been treated as a joint input in a production process. This omission in previous work is crucial whenever the extraction and use of a natural resource calls for simultaneous use of an environmental resource. The true scarcity value, $\mu = \mu_1 + \mu_2$, is larger than the traditional measure of resource scarcity, μ_1. However, it is important to note that μ does not represent the scarcity value of a resource *in situ*, but rather the scarcity value of a resource "in-use."

IV. ECONOMETRIC SPECIFICATION

The procedure for estimating the μ_i's as advanced by Halvorsen and Smith [9] has been adopted. Following the "duality" approach, the dynamic net surplus maximization problem of a competitive firm is recast in a static, cost minimization framework that is consistent with the intertemporal control problem.[3]

Assume that there exists n extraction and/or processing firms and that the representative firm's problem is to minimize total cost, or

$$\underset{\{K^u\}}{\text{Min}}\, K = \sum_{m=1}^{n} W_m K_m^u \tag{11}$$

subject to:

$$Y = Y(N, E, K^P, T) \tag{12}$$

$$N = N(X, E, K^e, T) \tag{13}$$

[3] Taylor shows that as long as the price path of a dynamic optimization problem does not follow a Stochastic Markov process, standard duality results, such as Hotelling's Lemma, can be applied [11]. In this analysis we do not make any explicit assumption about the price path (rather, implicitly assume that it is non-Markovian) and thus duality approach, as applied by Halvorsen and Smith [9], will be consistent with the primal dynamic net surplus maximization problem.

where u = P and E; m = 1, 2, ... n. The variable W_m is the hiring price of the composite capital-labor input and is assumed to be the same for both K^P and K^e. Equations (11) through (13) can be expressed as the Lagrangian function

$$L = W_m K_m^u + \theta_1 [Y - Y(N, E, K^P, T)] + \theta_2 [N - N(X, E, K^e, T)] \qquad (14)$$

The two Lagrangian multipliers of this problem, θ_1 and θ_2, can be interpreted as the shadow prices associated with the optimal level of Y and N, respectively. The solution to this cost minimization problem yields the reproducible cost function,

$$CR = CR(Y, W, N, X, E, T) \qquad (15)$$

Unfortunately, data on the stock or assimilative capacity of environmental resources are generally not available. Therefore, pollution abatement costs are used as a proxy for a loss of the assimilative capacity of the environment. While numerous estimates are available on the quantities of extractible resources, none really provide a definitive measure of the resource stock. Therefore, the reproducible cost function estimated in this analysis is reduced to CR(Y, W, N, E, T).

Applying Hotelling's Lemma[4] and utilizing the results of the cost minimization problem leaving "N" unrestricted, the shadow price of the extractible resource becomes the negative of the partial derivative of CR with respect to the output of the extraction subproduction functions, or

$$\frac{\partial CR}{\partial N} = -\bar{\mu}. \qquad (16)$$

In the actual estimation process, a translog functional form was used because of its inherent flexibility. The empirical model was,

$$\ln CR = a_o + a_y \ln Y + \sum_i a_i \ln W_i + a_N \ln N + a_T T + 1/2 [byy(\ln Y)^2 + \sum_{ij}\sum \ln W_i \ln W_j + b_{NN}(\ln N)^2 + b_{TT}T^2] + \sum_i C_{iy} \ln W_i \ln Y + \sum_i C_{iN} \ln W_i \ln N + \sum_i C_{iT} \ln W_i T + C_{yN} \ln Y \ln N + C_{yT}(\ln Y)T + C_{NT}(\ln N)T \qquad (17)$$

where W is the vector of input prices; i = capital (k), labor (l), the extractible resource (N) and the environmental resource (E).

The cost function must be homogeneous of degree one in prices in order to correspond to a well-behaved production function [13]. This provision, when coupled with the symmetry condition, implies the following set of restrictions on the parameters:

$$\sum_i a_i = 1 \quad \text{and} \quad \sum_i b_{ij} = \sum_j b_{ji} = 0 \qquad (18)$$

[4] See Diewert for a detailed discussion [12].

where i, j = k, l, N and E. A further assumption of Hick's neutral technical change imposes the following restrictions on the cost function:

$$C_{iT} = 0 \quad \text{and} \quad C_{yT} = 0 \tag{19}$$

where i = k, l, N and E.

Since the assumption of separability is crucial in this analysis, a test for weak separability of the production function, or its dual cost function, was developed following Brendt and Christensen [14, 15], Brendt and Wood [16] and McFadden [17]. The production function is weakly separable in N(•) and the other inputs. A test for weak separability is needed, however, for subaggregates of the production function or its dual cost function, i.e., $CR[(N, W_E), W, Y]$. The following restriction on the coefficients serves as a test of the weak separability hypothesis;

$$(N, W_E) - W - Y \Rightarrow C_{NY} = C_{EY} = C_{KY} = C_{LY} = 0;$$

$$(N, W_E) - Y - W \Rightarrow C_{KN} = C_{LN} = b_{KE} = b_{LE} = C_{KY} = C_{LY} = 0;$$

$$\text{and} \quad W - Y - (N, W_E) \Rightarrow C_{NY} = C_{EY} = b_{KN} = b_{LN} = b_{KE} = b_{EL} = 0 \tag{20}$$

The hypothesis of weak separability is tested by constructing an F-statistic based on the model estimated with and without the restrictions imposed on the parameter as suggested by Maddala [18], or

$$F = \frac{RRSS - URSS/r}{URSS/(n-k-1)} \tag{21}$$

where RRSS and URSS stand for the restricted residual sum of squares and the unrestricted residual sum of squares of the regression model, respectively, and where r, n and k represent the number of restrictions, the number of observations and the number of regressors in the model, respectively. Finally, in the course of estimating the model, a disturbance term is added to Equation 17 with the following assumptions regarding the error term:

$$E(U_{it}^2) = \sigma^2, \; E(U_{it}U_{jt}) = 0 \text{ for all } i \neq j, \text{ and } U_{it} = \rho_i U_{i,t-1} + E_{it} \tag{22}$$

where

$$E_{it} \sim N(0, \sigma_i^2); \quad U_{i0} \sim N\left(0, \frac{\sigma_i^2}{1-\sigma_i^2}\right); \quad \text{and}$$

$$E(U_{i,\,t-1}, \epsilon_{jt}) = 0 \text{ for all } i, j \tag{23}$$

This specification follows the assumption that the error term could be cross-sectionally heteroskedostic and time series autoregressive [AR(1)]. The negative of the partial derivative of the estimated cost function with respect to N yield the shadow price of the extractible resource, or

$$\frac{d(\ln CR)}{d(\ln N)} = -\frac{dCR}{dN} \cdot \frac{N}{CR} \tag{24}$$

Under an assumption of no environmental damage (Scenario I), the model estimated was

$$\begin{aligned} \ln CR = {} & a_o + a_y \ln Y + a_K \ln W_k + a_L \ln W_l + a_N \ln W_N + b_N \ln N + a_T T \\ & + 1/2\,[byy(\ln Y)^2 + b_{KK}(\ln W_K)^2 + b_{LL}(\ln W_L)^2 + b_{NN}(\ln W_N)^2 \\ & + 2b_{KL}\ln W_K \ln W_L + 2b_{KN}\ln W_K \ln W_N + 2b_{LN}\ln W_L \ln W_N + b_{TT}T^2\,] \\ & + C_{KN}\ln W_K \ln N + C_{LN}\ln W_L \ln_N + C_{NN}\ln W_N \ln N + U_t \end{aligned} \tag{25}$$

Shadow prices were derived from the following equation,

$$\frac{dCR}{dN} = -(a_N + C_{KN}\ln W_K + C_{LN}\ln W_L + C_{NN}\ln W_N)\,\frac{CR}{N} \tag{26}$$

Environmental costs were incorporated in the model (Scenario II) by the addition of a W_E term, or

$$\begin{aligned} \ln CR = {} & a_o + a_y \ln Y + a_K \ln W_K + a_L \ln W_L + a_N \ln W_N + a_E \ln W_E + b_N \ln N + a_T T \\ & + 1/2\,[byy(\ln Y)^2 + b_{KK}(\ln W_K)^2 + b_{LL}(\ln W_L)^2 + b_{NN}(\ln N)^2 + b_{EE}(\ln W_E)^2 \\ & + 2b_{KL\ln W}K\ln W_L + 2b_{KN}\mathrm{lkn}W_K \ln W_N + 2b_{KE}\ln W_K \ln W_E + 2b_{LN}\ln W_L \ln W_N \\ & + 2b_{LE}\ln W_L \ln W_E + 2b_{NE}\ln W_N \ln W_E + b_{TT}T^2\,] + C_{KN}\ln W_K \ln N \\ & + C_{LN}\ln W_L \ln N + C_{NN}\ln W_N \ln N + C_{EN}\ln W_E \ln N + U_t \end{aligned} \tag{27}$$

As noted above, the shadow price was estimated from

$$\frac{dCR}{dN} = -(a_N + C_{KN}\ln W_K + C_{LN}\ln W_L + C_{NN}\ln W_N + C_{EN}\ln W_E)\,\frac{CR}{N} \tag{28}$$

Under both scenarios, [Eq. (26) and Eq. (28)] the parameters within the parentheses were obtained directly from the estimating equations.[5]

V. THE DATA

Cost data from coal-fired electrical power plants were gathered for the period 1940 through 1985. Annual plant construction and production expenditures were obtained from the Federal Power Commission [20, 21] and the Energy Information Administration [20, 22-25]. Ten plants were selected for each year using a simple random sampling without replacement (SRSWOR) method. A total of 460 observations were used for this period. The price of coal and cost of

[5] Since exponentiation results in bias, a technique suggested by Goldberger has been followed [19].

labor was also taken from Federal Power Commission and Energy Information sources cited previously. The quantity of coal used for electrical power generation was taken from the Energy Information Administration [20, 22-25]. The price of capital was calculated using the concept of service price of capital as suggested by Christensen, et al. [26]. Following the imposition and modification of emission standards in 1969, and 1976, respectively, coal-fired electric power plants were compelled to control particulate, nitrogen, sulfur and related emissions. Actual pollution control investment and operating cost data from 1969 through 1985 were obtained from Southern California Edison [27], supported by various Electric Power Research Institute (EPRI) publications [28-31]. For purposes of this analysis, it was assumed that all coal-fired generating plants included in the sample incurred similar expenses and that such expenses were consistent with the environmental damages incurred.[6]

VI. RESULTS

Following Brendt and Christensen [14], a test for separability was constructed for the estimating equations. Results are reported in Table 1. Since none of the F-statistics are significant at the 5 percent level, the hypothesis of weak separability in the cost function cannot be rejected.

The shadow prices of coal in use, as estimated from Eq. (26), and (28) are reported in Table 2 and illustrated in Figure 1 for the period 1940 through 1985. Other commonly used measures of resource scarcity, i.e., real market price and real unit extraction cost, are also given for comparative purposes. The real market price of coal remained virtually unchanged from 1940 until 1970. It then doubled within a five year period, 1970 to 1975. Since 1975, real market prices for coal have remained fairly constant.

Real unit extraction costs have generally declined since 1940, although an upward shift occurred in the early 1970s. This result is consistent with results for many other extractive resources as noted by Barnett and Morse [32] and Johnson, Bell and Bennett [33].

Table 1. Test Statistics for Separability

Restriction	*F-Statistic*	*Tabulated F (5% Level)*
$(N, W_E) - W - Y \Rightarrow C_{NY} = C_{KY} = C_{EY} = C_{LY} = 0$	.72	2.37
$(N, W_E) - Y - W \Rightarrow C_{KN} = C_{NN} = C_{KY} = C_{LY} = 0$	.38	2.10
$W - Y - (N, W_E) \Rightarrow C_{NY} = C_{EY} = b_{KN} = b_{LN} = b_{KE} = b_{EL} = 0$	.37	2.37

[6] Admittedly, this is a heroic assumption. However, environmental damage estimates are generally unavailable. Actual plant costs are simply used to illustrate the differences between traditional measures and the more general measure proposed here.

Table 2. A Comparison of Various Prices/Indices of Coal Scarcity, 1940–1985.

	Real Market Price of Coal		Real Unit Extraction Cost of Coal		Scenario I Estimated Real Shadow Price of Unextracted Coal		Scenario II[a] Estimated Real Shadow Price of Coal in Use	
Year	Actual	Index	Actual	Index	Actual	Index	Actual	Index
1940	22	58.84	16	165.98	21	275.59		
	23	61.51	15	155.60	17	223.10		
	22	58.84	16	165.98	19.8	259.84		
	23	61.51	15	155.60	13.5	177.17		
	24	64.19	15	155.60	16.26	213.39		
1945	26	69.54	15	155.60	10.7	140.42		
	25	66.86	15	155.60	6.5	85.30		
	25	66.86	14	145.23	18.47	242.39		
	28	74.89	14	145.23	15.49	203.28		
	28	74.89	15	155.60	14.47	189.90		
1950	27	72.21	14	145.23	6.7	87.93		
	25	66.86	13	134.85	19	249.34		
	25	66.86	13	134.85	17.3	227.03		
	26	69.54	12	124.48	22.66	297.38		
	24	64.19	11	114.11	15.16	198.95		
1955	23	61.51	11	114.11	14.84	194.75		
	24	64.19	12	124.48	10.78	141.47		
	25	66.86	12	124.48	13.37	175.46		
	24	64.19	11	114.11	13.8	181.10		
	23	61.51	10	103.73	15.8	207.35		
1960	23	61.51	10	103.73	11	144.36		
	22	58.84	9	93.36	11.6	152.23		
	22	58.84	8	82.99	12.5	164.04		
	21	56.16	8	82.99	8.7	114.17		
	21	56.16	8	82.99	11.9	156.17		
1965	21	56.16	8	82.99	12.5	164.04		
	21	56.16	8	82.99	10.4	136.48		
	21	56.16	7	72.61	9.21	120.87		
	21	56.16	7	72.61	9.7	127.30		
	22	58.84	7	72.61	7.5	98.43		
1970	32.6	87.19	8.24	85.48	9	118.11		
	35.6	95.13	9	93.36	9.53	125.07	11.02	72.073
	37.4	100.00	9.64	100.00	7.62	100.00	15.29	100
	39.3	105.19	9.23	95.75	7.94	104.20	6.79	44.408
	67.6	180.80	8.02	83.20	11.03	144.75	27.37	179.01
1975	76.0	203.37	11.0	113.80	8.26	108.40	21.77	142.38
	73.2	195.75	11.7	121.16	13.37	175.46	27.51	179.92
	71.4	190.85	11.8	121.89	8.59	112.73	17.97	117.53
	74.2	198.48	11.3	117.12	6	78.74	20.58	134.60
	73.4	196.36	11.8	122.72	11.87	155.77	40.65	265.86
1980	69.9	186.89	10.3	106.95	10.4	136.48	69.2	452.58
	68.7	183.85	9.55	99.07	13.4	175.85	70.4	460.43
	67.2	179.59	9.95	103.22	10.95	143.70	67.9	444.08
	68.7	183.61	10.6	109.81	3.86	50.66	69.57	455.00
	74.6	199.44	10.4	108.35	2.6	34.12	81.59	533.62
1985	69.8	186.68	10.2	105.48	3.4	44.62	104.8	685.68

[a] An estimated real shadow price of coal in use (Scenario II) does not exist prior to 1971 because pollution controls had not yet been mandated.

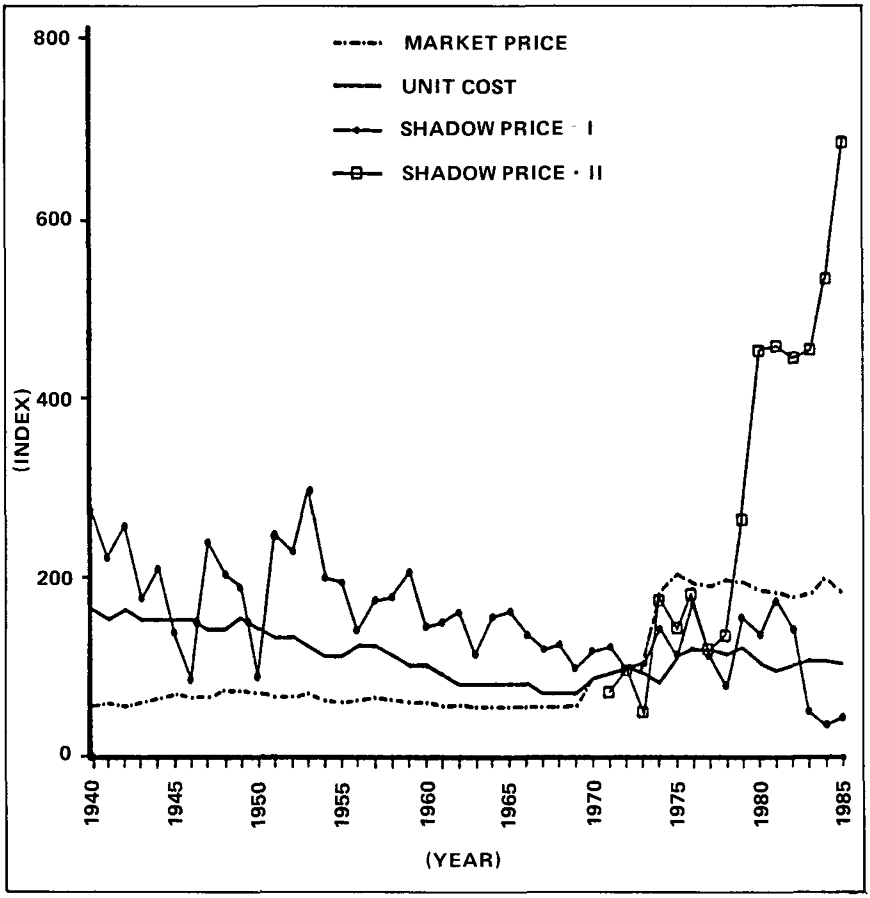

Figure 1. A comparison of common measures of resource scarcity for coal, 1940-1985.

The estimated real shadow price under Scenario I, in which no environmental losses were accounted for, generally declined over time. This result is consistent with the work of Slade [34], Manthy [35], and Smith [36], although the shadow price of coal in this analysis does not exhibit the same U-shaped pattern evident in these other analyses. The imposition of environmental regulations in the late 1960s, e.g., Scenario II, resulted in nearly an eight-fold increase in the real shadow price of coal in-use. A significant jump occurred in the late 1970s, a period of time in which extraordinarily high interest rates were experienced. Pollution abatement requires enormous initial physical and capital investments, so the shadow price of coal in use would be expected to increase during times of high capital costs. To the extent that the pollution abatement regulations were intended to internalize at least a portion of the negative externalities associated with power operation, it appears that they have been effective even though such regulations will not necessarily result in the optimal level of pollution control as noted earlier.

VII. CONCLUSIONS

In the event of a simultaneous use of extractive and environmental resources, traditional measures of resource scarcity understate the full cost of resource extraction and use and may result in a misallocation of resources. A measure of scarcity developed herein, which reflects the simultaneous, joint use of extractive and environmental resources, provides a more accurate representation of scarcity and includes previously determined measures as special cases.

The scarcity rent of coal used in the electrical power generation industry was derived from a translog reproducible cost function under conditions of simultaneous coal and environmental resource use. This measure was compared to other common measures of scarcity including real market price, real unit extraction cost and real scarcity rent, assuming no environmental loss. Scarcity rent of coal and unit extraction costs generally declined from 1940 through 1985, though unit extraction costs increased in more recent years. Real market prices were stable until the early 1970s, when an increase was noted. The scarcity-rent of coal under conditions of joint use with the environment, i.e., when environmental costs did occur increased significantly following the 1976 modifications of the emission standards and continued to increase sharply through 1985, indicating increasing scarcity of coal in-use.

The measure of scarcity developed in this analysis does not represent the rent of coal *in situ*. Rather, it reflects the scarcity of both the environment and coal when used simultaneously and may be useful in identifying the full costs of resource use. While more accurate estimates of the real costs of environmental pollution are needed in order to determine an optimal level of pollution control, the approach suggested here provides a basis for further work.

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