Environmental Concerns and Natural Resource Scarcity: The Case of Coal

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THE CASE OF COAL

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and

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Introduction

An increasing awareness of environmental pollution and its relative impact on mankind have elicited normative and positive economic models that address particular trade-offs between material objects and the maintenance of the environment. The existing literature has primarily been concerned with identifying the optimal amount of socially desirable pollution. However, the issue of natural resource scarcity, when viewed in conjunction with the availability of environmental resources or related amenities, seems to have attracted only minimal attention thus far. Leading natural resource economists like V. K. Smith (1981), John V. Krutilla and Anthony C. Fisher (1975), and Anthony C. Fisher (1979) have occasionally pointed out that research efforts need to be directed toward the question of jointness between an extractible and an environmental resource in a theoretical and empirical evaluation of natural resource scarcity.

This paper represents an attempt to respond to those suggestions. In this paper the determination of resource scarcity is evaluated both theoretically and empirically as the resource is being used. Conceptually, this could be achieved by looking at a resource in question either as an end product or as an intermediate product. In both cases, the extractible natural resource is used along with the environmental resource and other primary inputs. The environmental resource or, in particular, the assimilative capacity of environment (e.g., air and water), is normally utilized as a repository of the wastes discharged
from the use of the extractible resource in the same production process. A scarcity indicator should reflect such jointness.

A deterministic optimal control model of an extractible and an environmental resource use is developed next. The shadow price (scarcity index) developed when jointness of use is considered is different from that of earlier models. This index captures previously developed indices as special cases. The treatment of natural resource scarcity as incorporated herein has a much broader application than previously developed measures.

As an empirical test, coal and the assimilative capacity of air are treated as two joint inputs in the production of electricity. A trans-log cost function for electricity generation has been estimated using cross section and time series pooled data for two different periods. When explicit concerns about environmental protection have been accounted for in the empirical model, shadow prices exhibit a different trend than is observed in cases where no such environmental concern is explicitly accounted for.

**An Optimal Control Model of Joint Resource Use**

Extraction and processing are assumed to be two separate economic activities competitive in all respects: ownership, extraction, processing, and utilization of an extractible and an environmental resource and sales of a final output other than the extracted resource. Both require the other joint input, environmental resource. However, in order to capture the total use of the environmental resource, it is assumed that the same firm (industry) performs both the activities in the process of production of a final output. It is further assumed that the market is composed of identical firms. Thus, the problem is
approached from a representative firm's point of view. This hypothe-
sized firm maximizes the net surplus from the sale of its final output
over an infinite time horizon. The net surplus is derived at each
instant of time by subtracting the cost of extraction and processing of
the extracted resource from the total revenue it generates from the sale
of the final output. The extraction cost function, $C(\cdot)$, is assumed to
be a decreasing function of the reserve levels, $C_x$, $C_{xx} < 0$, and $C_e$,
$C_{ee} < 0$ and an increasing (at a decreasing rate) function of the amount
of extraction $C_N > 0$ and $C_{NN} < 0$. In particular, the cost function is
smooth and has twice differentiable continuous derivatives. The produc-
tion function $Y(\cdot)$ is assumed to be separable in the extracted output,
$N(\cdot)$ and other inputs, and have smooth and twice differentiable con-
tinuous derivatives. More specifically, $Y_N > 0$, $Y_{NN} < 0$, $Y_e > 0$,
$Y_{ee} > 0$, $Y_{K^P} > 0$, $Y_K^P K^P < 0$, $Y_T > 0$, and $Y_{TT} < 0$.

The net surplus function can be constructed as:

$$V = P_y Y(N(x, e, K^E, T), e, K^P, T) - W \sum K_i^P - \alpha C(N, x, e, W, T)$$

(1)

Letting $P_y$, $K^E$, $K^P$, $N$, $T$ be the price of the final product exogeneously
given to the firm (industry), composite capital-labor used in the
extraction and in processing the amount of the extracted input and
technology, respectively.

The competitive equilibrium is given by:

$$\max V = \int_{0}^{\infty} e^{-rt} \left[ P_y Y(N(x, e, K^E, T), e, K^P, T) - W \sum K_i^P - \alpha C(N, x, e, W, T) \right] dt$$

(2)

Subject to:

$$\frac{dx}{dt} = f(x) - N(x, e, K^E, T)$$

(3)
\[
\begin{align*}
\frac{de}{dt} &= ye - N(x, e, KE, T) \quad \ldots \quad (4)
\end{align*}
\]

and the initial conditions
\[
\begin{align*}
X(0) &= X_0 > 0 \quad \ldots \quad (5) \\
e(0) &= e_0 > 0 \quad \ldots \quad (6)
\end{align*}
\]

It is also assumed that for any time interval, 
\[
[a, b], N(t) \neq 0 \quad \ldots \quad (7)
\]
and \(0 < \alpha, \gamma \leq 1\).

Since price \(P_y\) is given to the firm, profit (net surplus) is maximized by controlling the level of \(KE\) in \(N(\cdot)\) and or \(KP\) in \(Y(\cdot)\).

The current value Hamiltonian for this problem is:
\[
H = P_y [N(X, e, KE, T), e, KP, T] \\
- W\Sigma K_i^P - \alpha C(N, x, e, W, T) + \mu_1[f(x) - N(x, e, KE, T)] \\
+ \mu_2[ye - N(x, e, KE, T)] \quad \ldots \quad (8)
\]

Note that \(\mu_1\) and \(\mu_2\) are the current value shadow prices associated with the level of stocks of the extractible and the environmental resource. These shadow prices can be interpreted as the marginal loss of current profit due to future extraction (use) of the resource and, thus, are recognized as the scarcity values of those resources.

The necessary first-order conditions yield:
\[
\begin{align*}
\mu_1 &= P_y YN - \alpha CN - \mu_2 \quad \ldots \quad (9) \\
P_y YKP &= W \quad \ldots \quad (10)
\end{align*}
\]

and
\[
\frac{d\mu_1}{dt} = [r - f'(x)] \mu_1 + \alpha CX \quad \ldots \quad (11)
\]
\[
\frac{d\mu_2}{dt} = (r - \gamma)\mu_2 - \gamma e + \alpha C_e
\]  \hspace{1cm} \ldots \text{(12)}

Equation (9) describes the fundamental efficiency condition in this competitive market of joint use of the extractible and the environmental resource. At any point along firm's optimal extraction and use path of both the extractible and the environmental resources, the marginal loss of profit \((\mu_1)\) is equated to the differences between the price of the extractible resource (i.e., value of the marginal product), the marginal cost of extraction, and the shadow price of the environmental resource. Rearranging equation (9),

\[
\mu_1 + \mu_2 = PyYN - \alpha CN
\]  \hspace{1cm} \ldots \text{(13)}

or,

\[
\mu = PyYN - \alpha CN
\]  \hspace{1cm} \ldots \text{(14)}

In traditional analysis of optimal resource extraction and use, \(\mu_2\) does not appear because the environmental resource and its use has never been treated as a joint input in the same production process. This omission in previous work is crucial since continuous extraction and use of an extractible resource calls for a simultaneous, continuous availability of the environmental resource. The moment the use of environmental resource is constrained, the use of the extractible resource becomes more costly. The marginal loss of profit due to not using one unit of the extractible resource increases by the amount of the marginal loss in profit due to not being able to utilize one unit of the environmental resource. Hence, the true scarcity value becomes \((\mu_1 + \mu_2)\) and will essentially be higher than \(\mu_1\), previously representing the full shadow or scarcity price. Traditional analyses have consistently underestimated the scarcity values of an extractible resource.
Empirical Model, Estimating Equations, Data and Results

Following the "duality" approach, the procedure of estimating the shadow price, \( \mu \), as advanced by Halvorsen and Smith (1984), has been adopted. The dynamic net surplus maximization problem of a competitive firm is recast in a static, cost minimization problem that is consistent with the intertemporal control problem.

Assume that the representative firm's problem is to minimize cost and there exists \( n \) firms. The objectives, then, is to:

Minimize \[ \sum_{i} W_i K^j_i \] \( \ldots \) (15)

Subject to \[ Y = Y(N, e, KP, T) \] \( \ldots \) (16)

\[ N = N(X, e, KE, T) \] \( \ldots \) (17)

where \( J = P, E \) and \( i = 1, 2, \ldots, n \)

The variable \( W_i \) is the hiring price of the composite capital labor input and is assumed to be same for both \((KP)\) and \((KE)\).

Equations (15) - (17) can be expressed as a Lagrangian function, such as that shown in equation (18).

\[ L = \sum_{i} W_i K^j_i + [Y - Y(N, e, KP, T)] + \mu[N - N(X, e, KE, T)] \] \( \ldots \) (18)

Note that \( \theta \) and \( \mu \) are the two Lagrangian multipliers of this problem. These two can be interpreted as the shadow prices associated with the optimal level of \( Y \) and \( N \), where \( Y \) and \( N \) represent the final output and the extracted natural resource, respectively.

The solution to this cost minimization problem yields the reproducible cost function (see Halvorsen and Smith, 1984).

\[ CR = CR(Y, W, N, X, e, T) \] \( \ldots \) (19)

Applying the Envelope Theorem and comparing the results of the cost
minimization problem with "N" unrestricted, one gets the shadow price of extractible resource, as shown in equation (20).

\[-\frac{\partial CR}{\partial N} = \rho \text{ . . . (20)}\]

The negative of the partial derivative of the reproducible cost function with respect to the output of the extraction subproduction function yields a shadow price.

**Econometric Specification and Estimation Technique**

In the reproducible cost function \( CR = CR(Y, W, N, X, e, T) \), \( W \) is the vector of input prices (e.g., capital, labor, and natural resources and the price of equipment and material used for protecting air pollution). However, due to data limitation on the stock of extractible and the environmental resource, we omit these two variables, \( X \) and \( e \), from the estimating equation.

We use the Translog, functional form in order to represent the reproducible cost function, \( CR(Y, W, N, T) \), which is

\[ \ln CR = a_0 + a_Y \ln Y + \sum_i a_i \ln W_i + a_N \ln N + a_T T \]

\[ + \frac{1}{2} [b_{yy}(\ln Y)^2 + \sum_{i,j} b_{ij} \ln W_i \ln W_j + b_{NN}(\ln N)^2 + b_{TT} T^2] \]

\[ + \sum_i c_{iy} \ln Y \ln W_i + c_{IN} \ln Y \ln N + \sum_i c_{iT} \ln W_i T \]

\[ + c_{YN} \ln Y \ln N + c_{YT}(\ln Y) T + c_{NT}(\ln N) T \text{ . . . (21)} \]

where \( i = K, L, n, e \).

\[ ^1 \text{See Silberberg (1978) for a detailed discussion of the Envelop Theorem.} \]
In order to correspond to a well-behaved production function, a cost function must be homogeneous of degree one in prices (i.e., for a fixed level of output, total cost must increase proportionately when all prices increase proportionately) (see Christensen and Greene, 1976). This and the symmetry condition together imply the following set of restrictions on the parameter:

\[ \sum a_i = 1 \]  \hspace{1cm} \ldots \hspace{1cm} (22)

\[ \sum b_{ij} = \sum b_{ji} = 0 \]  \hspace{1cm} \ldots \hspace{1cm} (23)

where \( i, j = K, L, n \) and \( e \).

Also, an assumption of Hicks' neutral technical change and homotheticity of the production function in reproducible inputs imply the following restrictions, such as,

\[ C_{iT} = 0 \]  \hspace{1cm} \ldots \hspace{1cm} (24)

and \( C_{yi} = 0; C_{yT} = 0 \)  \hspace{1cm} \ldots \hspace{1cm} (25)

where \( i = K, L, N, e \).

Thus, the translog cost function in equation (21) with the homotheticity and Hicks' neutrality assumptions imposed reduces to:

\[
\ln CR = a_0 + a_y \ln Y + a_K \ln W_K + a_L \ln W_L + a_n \ln W_n + a_e \ln W_e + a_N \ln N + a_T T + \frac{1}{2} \left[ b_{yy} (\ln Y)^2 + b_{KK} (\ln W_K)^2 + b_{LL} (\ln W_L)^2 \right. \\
+ b_{nn}(\ln W_n)^2 + b_{ee}(\ln W_e)^2 + 2 b_{KL} \ln W_K \ln W_L + 2 b_{Kn} \ln W_K \ln W_n \\
+ 2 b_{Ke} \ln W_K \ln W_e + 2b_{Ln} \ln W_L \ln W_n + 2b_{Le} \ln W_L \ln W_e \\
+ 2b_{ne} \ln W_n \ln W_e + b_{TT} T^2] + C_{KN} \ln W_K \ln N + C_{LN} \ln W_L \ln N \\
+ C_{nN} \ln W_n \ln N + C_{eN} \ln W_e \ln N \]  \hspace{1cm} \ldots \hspace{1cm} (26)

In order to estimate equation (26) econometrically from a cross sec-
tional and time series pooled data set, a disturbance term is added to the above equation with the following assumptions regarding the error term.

\[ E(U_{it}^2) = \sigma_i^2 \quad \ldots \quad (27) \]
\[ E(U_{it} U_{jt}) = 0, \text{ for } i \neq j \quad \ldots \quad (28) \]
and \[ U_{it} = \rho_i U_{i, t-1} + \varepsilon_{it} \quad \ldots \quad (29) \]
where \( \varepsilon_{it} \sim N(0, \sigma_{\varepsilon_i}^2) \) \quad \ldots \quad (30)

and \( U_{i0} \sim N(0, \frac{\sigma_{\varepsilon_i}^2}{1 - \rho_i^2}) \) \quad \ldots \quad (31)
and \[ E(U_{i, t-1}, \varepsilon_{jt}) = 0 \text{ for all } i, j \quad \ldots \quad (32) \]

This way of specifying the characteristics of the disturbance term is due to our assumption that the error term in our estimating equation could be cross sectionally heteroskedastic and time series wise autoregressive (AR(1)).

In order to calculate the shadow prices from the estimated reproducible cost function, equation (20) is referred to again. In that equation it has been shown that the negative of the partial derivative of the estimated cost function with respect to \( N \) yields shadow price. This is obtained as follows:

Differentiating \( \ln CR \) with respect to \( N \) yields:

\[ \frac{d}{d (\ln N)} = \frac{d CR}{d N} \cdot CR \quad \ldots \quad (33) \]

Now, the left-hand side can be obtained from equation (26).

**Data and Estimating Equation and Result**

For estimation purposes, cost data associated with generating electricity where coal is the major source of fuel in the United States
during the period 1940-82 is used. Historical steam electric plant construction costs and production expenditures reported annually by Federal Power Commission (1949, 1948-1976, and 1976) and then by Energy Information Administration (1977-1978, 1979-1981, and 1982) are the major sources of our information. Ten plants were selected for each year by using the simple random sampling without replacement (SRSWOR) method and have a total of 430 observations for this outline period. The entire period is split into two periods: 1940-69 and 1970-82 because prior to 1970, coal-fired electricity generating plants were not subjected to environmental regulations and assumed to have incurred very little expenditure on controlling sulphur oxide, nitrus oxide, and other particulate emission from burning coal. Thus, the use of environmental resource (air) was virtually free to the electricity generating plants. However, EPA's regulations and specification of standards regarding various oxides and particulate emissions in 1969 and then in 1976 probably compelled the coal-fired electric power plants to incur additional expenditures to control such emissions. Hence, the use of the environmental resource since that time have become more costly.

In order to accommodate this fact in the estimates of shadow prices, equation (26) has been modified for the scenario where environmental concerns are missing, i.e., the variable $W_e$ is dropped from the reproducible cost function. In that situation the estimating cost equation is:
Scenario I:  
(1940-69)

\[ L_nCR = a_o + a_y \ln Y + a_k \ln W_K + a_l \ln W_L + a_n \ln W_n + a_N \ln N \]
\[ + a_T T + \frac{1}{2} [b_{yy} (\ln Y)^2 + b_{KK}(\ln W_K)^2 + b_{LL}(\ln W_L)^2 + b_{nn}(\ln W_n)^2 \]
\[ + 2b_{KL} \ln W_K \ln W_L + 2 b_{Kn} \ln W_K \ln W_n + 2 b_{Ln} \ln W_L \ln W_n + b_{TT} T^2] \]
\[ + c_{Kn} \ln W_K \ln N + c_{LN} \ln W_L \ln N + c_{nN} \ln W_n \ln N + Ut \]  
\[ \ldots (34) \]

The shadow prices are finally calculated by using the following equation:

\[ \frac{dCR}{dN} = (a_N + c_{Kn} \ln W_K + c_{LN} \ln W_L + c_{nN} \ln W_n)^2 \]
\[ \ldots (35) \]

The required shadow prices are thus obtained just by taking the negative of the right-hand side of equation (35). Note that the parameters under the parentheses of equation (35) are obtained directly from the estimated regression equation. The estimated shadow prices are compared with other measures of scarcity, such as the unit cost of coal production and the market price, and are reported in Table 1 and plotted in Figure 1.

Since there is a difference in the estimating reproducible cost function, so there will be also a difference in the estimating equation for the shadow prices. The estimating cost equation under this scenario is:

\[ ^2CR \text{ is the estimated cost function. Since exponentiation results in bias, Goldberger's suggested technique has been followed.} \]
Table 1: Scarcity Indexes for Coal During 1940-1969

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated Real Shadow Price of Unextracted Coal ($/mln btu)</th>
<th>Real Market(^1) Price of Coal ($/mln btu)</th>
<th>Real Unit(^2) Extraction Cost of coal ($/mln btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual Index (1970=100)</td>
<td>Actual Index (1970=100)</td>
<td>Actual Index (1970=100)</td>
</tr>
<tr>
<td>1940</td>
<td>0.47 235.0</td>
<td>0.22 67.0</td>
<td>0.16 194.0</td>
</tr>
<tr>
<td>1941</td>
<td>0.43 215.0</td>
<td>0.23 71.0</td>
<td>0.15 182.0</td>
</tr>
<tr>
<td>1942</td>
<td>0.38 190.0</td>
<td>0.22 67.0</td>
<td>0.16 194.0</td>
</tr>
<tr>
<td>1943</td>
<td>0.36 180.0</td>
<td>0.23 71.0</td>
<td>0.15 182.0</td>
</tr>
<tr>
<td>1944</td>
<td>0.36 180.0</td>
<td>0.24 74.0</td>
<td>0.15 182.0</td>
</tr>
<tr>
<td>1945</td>
<td>0.35 175.0</td>
<td>0.26 80.0</td>
<td>0.15 182.0</td>
</tr>
<tr>
<td>1946</td>
<td>0.25 125.0</td>
<td>0.25 77.0</td>
<td>0.15 182.0</td>
</tr>
<tr>
<td>1947</td>
<td>0.22 110.0</td>
<td>0.25 77.0</td>
<td>0.14 170.0</td>
</tr>
<tr>
<td>1948</td>
<td>0.23 115.0</td>
<td>0.28 86.0</td>
<td>0.14 170.0</td>
</tr>
<tr>
<td>1949</td>
<td>0.23 115.0</td>
<td>0.28 86.0</td>
<td>0.14 170.0</td>
</tr>
<tr>
<td>1950</td>
<td>0.22 110.0</td>
<td>0.27 83.0</td>
<td>0.14 170.0</td>
</tr>
<tr>
<td>1951</td>
<td>0.18 90.0</td>
<td>0.25 77.0</td>
<td>0.13 158.0</td>
</tr>
<tr>
<td>1952</td>
<td>0.22 110.0</td>
<td>0.25 77.0</td>
<td>0.13 158.0</td>
</tr>
<tr>
<td>1953</td>
<td>0.23 115.0</td>
<td>0.26 80.0</td>
<td>0.12 146.0</td>
</tr>
<tr>
<td>1954</td>
<td>0.23 115.0</td>
<td>0.24 74.0</td>
<td>0.11 133.0</td>
</tr>
<tr>
<td>1955</td>
<td>0.24 120.0</td>
<td>0.23 71.0</td>
<td>0.11 133.0</td>
</tr>
<tr>
<td>1956</td>
<td>0.21 105.0</td>
<td>0.24 74.0</td>
<td>0.12 146.0</td>
</tr>
<tr>
<td>1957</td>
<td>0.20 100.0</td>
<td>0.25 77.0</td>
<td>0.12 146.0</td>
</tr>
<tr>
<td>1958</td>
<td>0.20 100.0</td>
<td>0.24 74.0</td>
<td>0.11 133.0</td>
</tr>
<tr>
<td>1959</td>
<td>0.20 100.0</td>
<td>0.23 71.0</td>
<td>0.10 121.0</td>
</tr>
<tr>
<td>1960</td>
<td>0.20 100.0</td>
<td>0.23 71.0</td>
<td>0.10 121.0</td>
</tr>
<tr>
<td>1961</td>
<td>0.20 100.0</td>
<td>0.22 67.0</td>
<td>0.09 109.0</td>
</tr>
<tr>
<td>1962</td>
<td>0.20 100.0</td>
<td>0.22 67.0</td>
<td>0.08 97.0</td>
</tr>
<tr>
<td>1963</td>
<td>0.20 100.0</td>
<td>0.21 64.0</td>
<td>0.08 97.0</td>
</tr>
<tr>
<td>1964</td>
<td>0.20 100.0</td>
<td>0.21 64.0</td>
<td>0.08 97.0</td>
</tr>
<tr>
<td>1965</td>
<td>0.20 100.0</td>
<td>0.21 64.0</td>
<td>0.08 97.0</td>
</tr>
<tr>
<td>1966</td>
<td>0.19 95.0</td>
<td>0.21 64.0</td>
<td>0.08 97.0</td>
</tr>
<tr>
<td>1967</td>
<td>0.19 95.0</td>
<td>0.21 64.0</td>
<td>0.08 97.0</td>
</tr>
<tr>
<td>1968</td>
<td>0.18 90.0</td>
<td>0.21 64.0</td>
<td>0.07 85.0</td>
</tr>
<tr>
<td>1969</td>
<td>0.18 90.0</td>
<td>0.22 67.0</td>
<td>0.07 85.0</td>
</tr>
</tbody>
</table>

\(^1\)Real market price of coal has been obtained by dividing the market price by the wholesale price index.

\(^2\)Real unit cost has been calculated by dividing the wage by output per manhour (labor productivity) and then deflated by the wholesale price index.
Figure 1. A plot of estimated real shadow price, real market price and real unit cost during 1940-1969.
Scenario II: (1970-82)

\[
\ln CR = a_0 + a_y \ln Y + a_K \ln W_K + a_L \ln W_L + a_n \ln W_n + a_e \ln W_e \\
+ a_N \ln N + a_T T + \frac{1}{2} [b_{yy} (\ln Y)^2 + b_{KK} (\ln W_K)^2 + b_{LL} (\ln W_L)^2] \\
+ b_{nn}(\ln W_n)^2 + b_{ee}(\ln W_e)^2 + 2 b_{KL} \ln W_k \ln W_L + 2 b_{Kn} \ln W_k \ln W_n \\
+ 2 b_{Ke} \ln W_k \ln W_e + 2 b_{Ln} \ln W_l \ln W_n + 2 b_{Le} \ln W_l \ln W_e \\
+ 2 b_{ne} \ln W_n \ln W_e + b_{TT} T^2] + C_{KN} \ln W_K \ln N + C_{LN} \ln W_L \ln N \\
+ C_{nN} \ln W_n \ln N + C_{eN} \ln W_e \ln N + U_t \\
\ldots \ldots (36)
\]

Finally, the shadow prices under the second scenario are obtained by taking the partial derivative of equation (36) with respect to \( N \), which yields:

\[
\frac{dCR}{dN} = (a_N + C_{KN} \ln W_K + C_{LN} \ln W_L + C_{nN} \ln W_n + C_{eN} \ln W_e) \frac{CR}{N} \\
\ldots \ldots (37)
\]

The estimated shadow prices are compared against alternative measures of scarcity, e.g., real market price and real unit cost, and are reported in Table 2 and plotted in Figure 2.

A hypothesis of the trend of the shadow price being positive for both the periods has been tested separately by regressing the shadow prices against time. For the first period, i.e., 1940-1969, the null hypothesis could not be accepted; while for the period 1970-1982, the null hypothesis could not be rejected on the basis of "t" statistics. The estimated regression equations are reported below.
Table 2: Scarcity Indexes for Coal During 1970-82

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated Real* Shadow Price of Unextracted Coal</th>
<th>Real Unit* Cost of Extraction of Coal</th>
<th>Real Market* Price of Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Index</td>
<td>Actual</td>
</tr>
<tr>
<td>1970</td>
<td>19.71</td>
<td>100.00</td>
<td>8.24</td>
</tr>
<tr>
<td>1971</td>
<td>19.46</td>
<td>98.73</td>
<td>9.00</td>
</tr>
<tr>
<td>1972</td>
<td>18.56</td>
<td>94.16</td>
<td>9.64</td>
</tr>
<tr>
<td>1973</td>
<td>15.39</td>
<td>78.08</td>
<td>9.23</td>
</tr>
<tr>
<td>1974</td>
<td>15.70</td>
<td>79.65</td>
<td>8.02</td>
</tr>
<tr>
<td>1975</td>
<td>18.10</td>
<td>91.83</td>
<td>10.97</td>
</tr>
<tr>
<td>1976</td>
<td>19.67</td>
<td>99.79</td>
<td>11.68</td>
</tr>
<tr>
<td>1977</td>
<td>18.18</td>
<td>92.24</td>
<td>11.75</td>
</tr>
<tr>
<td>1978</td>
<td>17.71</td>
<td>89.85</td>
<td>11.29</td>
</tr>
<tr>
<td>1979</td>
<td>19.92</td>
<td>101.06</td>
<td>11.83</td>
</tr>
<tr>
<td>1980</td>
<td>19.20</td>
<td>97.41</td>
<td>10.31</td>
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<tr>
<td>1981</td>
<td>22.92</td>
<td>116.29</td>
<td>9.55</td>
</tr>
<tr>
<td>1982</td>
<td>21.93</td>
<td>111.26</td>
<td>9.95</td>
</tr>
</tbody>
</table>

*The actual real shadow price, the real marginal extraction cost and the real market price are in cents per million b.t.u.
Figure 2. A plot of real market price, estimated real shadow price and real unit cost during 1970-1982.
Period I:
\[
\mu_t = 0.3553 - 0.0071T \\
(19.8541)* (-7.0104)* 
\]

Period II:
\[
\mu_t = 17.0012 + 0.2795T \\
(15.3420)* (2.0020)* 
\]

Note that in equations (38) and (39) \( \mu_t \) and \( T \) represent the shadow price and time, respectively.

In Table 1 and Figure 1, the estimated shadow prices are compared with alternative measures of natural resource scarcity. It is shown that the estimated shadow prices have fallen significantly whereas the market price of coal has remained more or less steady at its 1940 level. The third measure of scarcity reported here, unit cost, exhibits a falling trend. The argument against unit cost as a valid measure of resource scarcity has been made by Brown and Field (1978). Consequently, the estimated shadow price and market price remain as possible candidates. A possible reason why the market price for coal cannot be accepted as a better measure than the estimated shadow price is that market prices are an average of spot price, contract price, and administered price and, as such, may not represent the true characteristics of competition. Hence, estimated shadow prices are preferred as the correct measure of resource scarcity. In the second period under study (1970-1982), estimated shadow prices, real market price, and the unit costs are reported in Table 2 and Figure 2. The preferred measure, shadow prices, indicate a slightly upward trend (see the trend regression coefficient in equation 39), whereas the market price of coal has

*"t" statistics are in the parentheses.
registered more than twofold increase. Notice that there is a sudden jump in the market price of coal in 1974, which was probably due to oil price shocks, and thereafter there is a falling trend. The market price of coal, as a measure of scarcity, during this period can be said to be an imperfect one and resulted in a distortion in a competing substitute market. On the other hand, the estimated shadow prices do not suffer from this type of problem and are preferred measures.

Two significant empirical conclusions result from this study. First, during 1940-1969 when environmental protection was not of much concern, coal in use, as exhibited by the estimated shadow price, was not relatively becoming scarce. Second, the result (for 1970-1982) suggests that due to the regulations by the Environmental Protection Agency, the coal-fired electric industries had to incur additional expenditure in order to use coal. The shadow prices corresponding to coal in-use increased during this interval. Thus, coal may be regarded as becoming relatively more scarce.

**Summary and Conclusions**

In this paper, it has been suggested that the concurrent use of extractible and environmental resources must be evaluated simultaneously in order to determine whether a natural resource is becoming more scarce. An optimal control framework is used in order to illustrate such joint use. Then, an index of scarcity (shadow price) is developed which treats earlier indexes of scarcity as special cases. Following duality approach, an empirical model is formulated and the shadow prices of coal in use are subsequently estimated. Following this analysis it
is recognized that a proper accounting of extractible resources in use will yield a different measure of resource scarcity than previously developed and used. However, additional empirical studies are required to further test the hypothesis advanced in this study.
References


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