Environmental Regulations and Productivity Growth: The Case of Fossil-Fueled Electric Power Generation

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Abstract

This paper measures and analyzes the effect of sulfur dioxide emission restrictions on the rate of productivity growth in the electric power industry over the 1973-1979 business cycle. A firm specific measure of regulatory intensity is developed which depends on the severity of the emission standard, the extent of enforcement, and the unconstrained emission rate relevant to each utility. The results indicate that emission regulations result in significantly higher generating costs, primarily from the increased use of low-sulfur fuels. The average rate of productivity growth was reduced by .59 percentage points per year for constrained utilities.

The Clean Air Act Amendments of 1970 set national air quality standards for major pollutants and established a framework for state regulation.[1] Since 1970 individual states have placed emission restrictions on an increasing number of industries and pollutants. It has been argued that these emission standards have adversely affected the performance of American industry, particularly its productivity growth, by diverting resources from the production of marketable output to the satisfaction of emission constraints.[2]

This paper analyzes and quantifies the effect of air pollution restrictions on productivity growth in one of the earliest and most widely affected industries, electric power generation. The paper focuses on emission standards for sulfur dioxide, the industry's major air pollutant. The opening section of the paper summarizes the development of the air pollution laws and outlines their application to electric utilities.

The process of identifying the productivity impact of emission regulations during the seventies is complicated by coincident major changes in market forces. The decade witnessed both an unprecedented increase in fuel prices and a dramatic decline in market growth for electric power. Between 1958 and 1969, the annual increase in the average price per million BTUs of fuel consumed by utilities was less than 0.3 percent. The same price increased more than 18 percent per year in the 1969-79 period and at nearly a 30 percent annual rate between 1973 and 1976.[3] If, as some economic research indicates, electric power generation is fuel-using, rising fuel prices have contributed to the industry's declining rate of technical change.[4] Over the same period market growth fell sharply. After increasing at a 7.6 percent annual rate in the 1958-69 period, kilowatt-hours sold to ultimate consumers by privately-owned electric utilities increased at an average annual rate of 4.6 percent during 1969-79 while falling to a 1.8 percent rate between 1973 and 1976.[5] If, as many believe, scale economies continued into the seventies, declining output growth has reduced the contribution of a traditional source of the industry's productivity growth.[6]

Confounding the pure market effect of rising fuel prices, the introduction of emission standards in the seventies encouraged utilities to switch from lower cost high-sulfur fuels to more expensive low-sulfur fuels. An important empirical objective of this research is to disentangle the regulatory and pure market determinants of the decline in productivity performance in electric power, a decline that has been substantial. Among the 45 sectors examined by Fraumeni and Jorgenson (1980), electric power ranked third in terms of average annual rates of productivity growth in the 1948-69 period but fell to thirty-fifth in the 1969-76 period.[7]

The underlying framework for this paper is an economic model of production and productivity growth. A formal model of the industry's technology is developed in section 2. The model not only isolates the components of productivity growth associated with scale economies, environmental regulations, and technical change but also distinguishes the effects of changing emission standards, shifting market demand, and changing input prices on each source of growth. The model treats low-sulfur and high-sulfur fuels as distinct inputs in order to separate the productivity effects of increasing fuel prices from regulation-induced switching to higher-priced low-sulfur fuel.

The model is used to analyze the economic growth of fifty-six electric utilities over the 1973-79 period, a complete business cycle. The research focuses on the productivity of fossil-fueled generation, the real target of environmental standards.

To implement the model, a measure of "regulatory intensity" is introduced.

To measure the impact of regulation on the firm it is not sufficient merely to account for the presence or level of an emission standard. In the electric utility industry statutory emission rates, the level of enforcement efforts, and the degree of compliance vary widely across firms. A measure of regulatory intensity is developed which accounts for all these characteristics. The complete data set and the estimating model are described in section 3.

The fourth section of the paper reports our empirical findings. Included are results of all hypothesis tests and estimates of the average yearly productivity consequences of environmental regulation, scale effects, and technical change. The main conclusion to be drawn from the research is that environmental regulations have had a significant negative impact on the rate of productivity growth in the electric utility industry over the 1973-79 period. On average, effective air pollution regulations reduced firm specific rates of productivity growth by .59 percentage points per year. Environmental regulations primarily have resulted in the increased use of low-sulfur fuels and capital with the main cost impact arising from the substitution from high-sulfur to low-sulfur fuels. Economies of scale are present in electric power generation but these have not made a large contribution to productivity growth because of low output growth rates over the period. Finally, an upward trend in the rate of technical change is responsible for most of the improvement in productivity growth in this industry during the late 1970s.

1. The Clean Air Act Amendments and Electric Utilities

With the goal of protecting public health, the Clean Air Act Amendments were passed by Congress in December 1970. The Amendments required the Environmental Protection Agency (EPA) to establish uniform national ambient air quality standards for major pollutants. In April 1971 the EPA published standards for six pollutants: sulfur oxides, nitrogen oxides, hydrocarbons, particulates, photochemical oxidants, and carbon monoxide. Each state then was required to submit a state implementation plan (SIP) which outlined how existing pollution sources would be regulated so that the national ambient air standards would be achieved by July 1975.[8] The majority of SIPs were approved by the EPA during 1972.

In 1970 coal-fired power plants were the source of more than 50 percent of the nation's sulfur dioxide emissions and as a result were one of the first pollution sources to be regulated.[9] Now, as then, the state plans vary greatly in both the stringency of the regulations and the method of regulation. Approximately one-third of the states restrict the percentage of sulfur in the fuel which each plant can burn. These states tend to be concentrated in the northeast and west. The remaining states focus on emission levels by limiting either the pounds of sulfur dioxide per million BTUs which each plant can emit or restricting the concentration of sulfur dioxide in the exhaust gas. In addition, approximately half of the states have established emission regulations which vary across geographic regions. In approximately one-third of the states the size of the generating source affects the allowed emission rate with larger sources generally being regulated more tightly. The type of fuel burned also affects allowed emissions in approximately one-third of the states. Oil-fired generators usually are controlled more strictly.

Generating plants built or modified after August 1971 face a uniform national emission standard of 1.2 pounds of sulfur dioxide per million BTUs of fuel input for coal-fired generators and .8 pounds per million BTUs for oil-fired generators. These new source performance standards allow plants to meet the emission restrictions by burning low-sulfur fuels. This was amended in 1978 so that new plants now also are required to install some type of emission desulfurization system.[10]

Enforcement of the SIPs is the responsibility of the states but the EPA has the power to intervene if the laws are not being enforced to its satisfaction. The diversity of regulations and enforcement levels has resulted in varying degrees of compliance and different emission rates across plants.

Understanding the response of utilities to these air pollution restrictions is important in analyzing potential productivity effects.[11] In general, utilities have lowered sulfur dioxide emissions by switching to higher-priced, lower sulfur fuels. The price effect can be substantial. In 1980, for example, low-sulfur fuel oil commanded a 35 percent price premium per million BTUs over high-sulfur oil.[12] If regulation-induced fuel switching results in higher costs with no corresponding increase in productive inputs, then productivity growth falls.

A smaller number of utilities have responded to environmental regulations by installing flue gas desulfurization systems, known as scrubbers, to clean the exhaust gases. By the end of 1980 scrubbers had been installed on all or part of the generating capacity of 47 plants. This compares with seven plants operating scrubbers at the end of 1975.[13] If the installation of scrubbers results in increased capital input with no corresponding increase in KWH production, there is a negative impact on productivity growth.

Other industry responses have been blocked. For example, the industry has argued for the use of higher stacks as a method of dispersing pollutants over a wider area but this control method has been rejected by the EPA because it does not reduce emissions. In addition, the industry has argued for the use of intermittent controls such as burning low-sulfur fuels only when weather conditions are apt to aggravate pollution problems. This method also has been rejected by the EPA in favor of continuous controls on pollution emissions.[14]

The utilities' method of pollution control has important implications for the model of firm technology developed in the next section. Specifically, fuel input is divided into low and high-sulfur components not only to capture the productivity effect of regulation-induced fuel switching but also to distinguish this regulatory effect from the pure market effect of rising fuel prices. Moreover, since environmental regulations can affect the demands for labor and capital inputs as well as the relative demands for low and high-sulfur fuels, the separability of regulatory intensity and fuel prices is not maintained.

2. Productivity Growth

The model of total factor productivity developed in this paper is based on a factor-minimal cost function for an electric utility.[15] Production cost (C) is assumed to be a twice-differentiable function of the input prices of labor (p_L), capital (p_K), low-sulfur fuel ($p_{F_{\ell s}}$), and high-sulfur fuel ($p_{F_{hs}}$), the output of kilowatt-hours (Q), regulatory intensity (R), and time (T):[16]

$$(1) \quad C = C(p_L, p_K, p_{F_{\ell s}}, p_{F_{hs}}, Q, R, T).$$

The model maintains that factor markets are competitive and that each utility must supply all electricity demanded at any given price. The arguments of the cost function are treated as exogenous variables. Input levels are endogenous. There are no a priori restrictions regarding homotheticity, scale economies, marginal rates of substitution, the form of technical change, or the mediums of regulatory impact.

Logarithmically differentiating the cost function (1) with respect to time decomposes the rate of growth of total cost into its source components:[17]

$$(2) \quad \frac{d\ell nC}{dT} = \Sigma \frac{\partial \ell nC}{\partial \ell np_i} \frac{d\ell np_i}{dT} + \frac{\partial \ell nC}{\partial \ell nQ} \cdot \frac{d\ell nQ}{dT} + \frac{\partial \ell nC}{\partial R} \cdot \frac{dR}{dT} + \frac{\partial \ell nC}{\partial T} .$$

The logarithmic partial derivatives appearing in (2) have particular economic interpretations. Applying Shephard's lemma, the elasticity of cost with respect to the price of each input equals the corresponding input's share(v_i) in total cost:

$$(3) \quad \frac{\partial \ell nC}{\partial \ell np_i}(p_L, p_K, p_{F_{\ell s}}, p_{F_{hs}}, Q, R, T) = \frac{p_i X_i}{C} \equiv v_i \qquad (i = L, K, F_{\ell s}, F_{hs}).$$

The elasticity of cost with respect to output (v_Q) can be interpreted as a measure of scale economies:

$$(4) \quad \frac{\partial \ell nC}{\partial \ell nQ}(p_L, p_K, p_{F_{\ell s}}, p_{F_{hs}}, Q, R, T) \equiv v_Q.$$

Constant returns to scale is implied by $v_Q = 1$; v_Q less (greater) than unity is consistent with scale economies (diseconomies). The semi-logarithmic derivative of cost with respect to regulatory intensity (v_R) represents the direct cost effect of tightened environmental regulations holding constant all input prices, scale, and the technology:

(5) $\frac{\partial \ell nC}{\partial R}(p_L, p_K, p_{F_{\ell s}}, p_{F_{hs}}, Q, R, T) \equiv v_R.$

Finally, the rate of technical change (v_T) is defined as the negative of the derivative of the logarithm of cost with respect to time:

(6) $\frac{-\partial \ell nC}{\partial T}(p_L, p_K, p_{F_{\ell s}}, p_{F_{hs}}, Q, R, T) \equiv v_T.$

Given this characterization of the utility's technology, the rate of productivity growth (v_G), defined as the negative of the rate of change in average production cost holding input prices constant

(7) $v_G \equiv -\left.\frac{d\ell n(C/Q)}{dT}\right|_p ,$

can be expressed in terms of the three sources of productivity growth. Subtracting the growth rate of output and weighted growth rates of input prices from both sides of (2) produces the relation between the rate of cost reduction associated with productivity growth and its three sources:

(8) $\left.\frac{d\ell n(C/Q)}{dT}\right|_p = \left(\frac{\partial \ell nC}{\partial \ell nQ} - 1\right)\frac{d\ell nQ}{dT} + \frac{\partial \ell nC}{\partial R}\cdot\frac{dR}{dT} + \frac{\partial \ell nC}{\partial T}$

so that, given (7),

(9) $v_G = \left(1 - \frac{\partial \ell nC}{\partial \ell nQ}\right)\frac{d\ell nQ}{dT} - \frac{\partial \ell nC}{\partial R}\cdot\frac{dR}{dT} - \frac{\partial \ell nC}{\partial T}$

$= (1 - v_Q)\frac{d\ell nQ}{dT} - v_R\frac{dR}{dT} + v_T,$

where v_G is the Divisia index number

(10) $v_G = -\left(\frac{d\ell nC}{dT} - \frac{d\ell nQ}{dT}\right) + \Sigma\, v_i \frac{d\ell np_i}{dT} .$

Equation (9) contains the sources and determinants of productivity growth. The first term in (9) equals the scale effect. It is a function of scale economies ($\partial \ell nC/\partial \ell nQ$) and output growth ($d\ell nQ/dT$). Productivity growth through the scale effect is characterized by a <u>movement along</u> the average cost curve. The second term represents the direct productivity effect of environmental regulations. It is the product of the marginal cost of increased regulation ($\partial \ell nC/\partial R$) and the extent of the change in regulatory intensity (dR/dT). This direct productivity effect is characterized by a <u>vertical displacement</u> of the average cost curve. The third term in (9) measures the productivity contribution of technical change. It too results in a shift of the average cost curve. An important objective of this paper is to decompose v_G into these three sources of productivity growth.

It is important to emphasize that the scale economy term $\partial \ell nC/\partial \ell nQ$, the regulatory impact derivative $\partial \ell nC/\partial R$, and the expression for the rate of technical change $\partial \ell nC/\partial T$ are not treated as constants. Each varies as a function of input prices, output, regulatory intensity, and time. This permits a more detailed evaluation of the effects of market forces and regulatory policy on productivity growth.

Empirical application of this model requires selection of a functional form to represent the cost function defined in (1). For this purpose, we consider the translog cost function:[18]

$$(11)\quad C = \exp[\beta_o + \sum_i \beta_i \ell np_i + \beta_Q \ell nQ + \beta_R R + \beta_T T + 1/2\sum_i\sum_j \gamma_{ij}\ell np_i \ell np_j$$

$$+ \sum_i \gamma_{iQ}\ell np_i \ell nQ + \sum_i \gamma_{iR}\ell np_i R + \sum_i \gamma_{iT}\ell np_i T + 1/2\gamma_{QQ}(\ell nQ)^2$$

$$+ \gamma_{QR}\ell nQR + \gamma_{QT}\ell nQT + 1/2\gamma_{RR}R^2 + \gamma_{RT}RT + 1/2\gamma_{TT}T^2].$$

Taking the logarithmic partial derivatives of (11) with respect to each input price and applying Shephard's lemma (3), the behavioral equations take the form[19]

$$(12)\quad v_i = \beta_i + \sum_j \gamma_{ij}\ln p_j + \gamma_{iQ}\ln Q + \gamma_{iR}R + \gamma_{iT}T \qquad (i = L, K, F_{\ell s}, F_{hs}).$$

Using (4), (5), and (6), the corresponding partial derivatives with respect to the logarithm of output, regulatory intensity, and time are, respectively,

$$(13)\quad v_Q = \beta_Q + \sum_j \gamma_{jQ}\ln p_j + \gamma_{QQ}\ln Q + \gamma_{QR}R + \gamma_{QT}T$$

$$(14)\quad v_R = \beta_R + \sum_j \gamma_{jR}\ln p_j + \gamma_{QR}\ln Q + \gamma_{RR}R + \gamma_{RT}T$$

$$(15)\quad -v_T = \beta_T + \sum_j \gamma_{jT}\ln p_j + \gamma_{QT}\ln Q + \gamma_{RT}R + \gamma_{TT}T.$$

Substituting (13), (14), and (15) into (9) yields an expression for v_G in terms of the translog parameters:

$$(16)\quad v_G = [1 - (\beta_Q + \sum_j \gamma_{jQ}\ln p_j + \gamma_{QQ}\ln Q + \gamma_{QR}R + \gamma_{QT}T)] \cdot \frac{d\ln Q}{dT}$$
$$- [\beta_R + \sum_j \gamma_{jR}\ln p_j + \gamma_{QR}\ln Q + \gamma_{RR}R + \gamma_{RT}T] \cdot \frac{dR}{dT}$$
$$- [\beta_T + \sum_j \gamma_{jT}\ln p_j + \gamma_{QT}\ln Q + \gamma_{RT}R + \gamma_{TT}T].$$

The cost function (11), the four behavioral equations (12), and the expression for v_G (16) form the complete model of economic growth in the electric power industry. All important hypotheses regarding the sources and determinants of productivity growth can be characterized in terms of the parameters appearing in this six-equation model. The principal hypotheses can be divided into sets corresponding to the three productivity source components: scale effects, regulatory impact, and technical change.

Scale effects. The most important scale hypothesis is whether production exhibits constant returns to scale, $v_Q = 1$. The seven parametric restrictions corresponding to constant returns for the translog cost function (11) can be derived directly from (13):[20]

$$(17) \quad \beta_Q = 1$$

$$\gamma_{LQ} = \gamma_{KQ} = \gamma_{F_{\ell s}Q} = \gamma_{QQ} = \gamma_{QR} = \gamma_{QT} = 0.$$

If this hypothesis cannot be rejected, then the scale effect, $(1 - v_Q)d\ell nQ/dT$ defined in (9), equals zero regardless of the extent of market growth. Given a horizontal average cost curve, changes in production levels ($d\ell nQ/dT$) have no effect on average cost and therefore productivity growth. Moreover, under constant returns, both γ_{QR} and γ_{QT} equal zero implying from (14) and (15), respectively, that neither regulatory impact nor technical change is sensitive to changes in the utility's scale of operation.

If the constant returns to scale hypothesis (17) is rejected, then the productivity consequences of market growth can be determined from (13). If $\partial\ell nC/\partial\ell nQ < 1$, proportional expansions in output produce less than proportional expansions in total cost. This indicates the presence of scale economies. It implies that market growth will lead to downward movements along the average cost curve or, stated equivalently, to higher productivity growth. Of course, the opposite conclusions follow from scale diseconomies which are implied by $\partial\ell nC/\partial\ell nQ > 1$.

The remaining interesting scale hypothesis for productivity analysis is homogeneity. It suggests that, while scale economies may be an important source of economic growth, its contribution is insensitive to the utility's scale of operation, to changes in any input price or regulatory policy, and even to particular periods in the firm's history. The necessary and sufficient restrictions can be derived directly from (13):

(18) $\gamma_{LQ} = \gamma_{KQ} = \gamma_{F_{\ell s}Q} = \gamma_{QQ} = \gamma_{QR} = \gamma_{QT} = 0.$

Regulatory impact. Changing environmental regulations are hypothesized to have productivity consequences. Should emission standards have neither direct nor indirect productivity effects, all regulation related parameters appearing in the cost function would equal zero:[21]

(19) $\beta_R = \gamma_{LR} = \gamma_{KR} = \gamma_{F_{\ell s}R} = \gamma_{QR} = \gamma_{RR} = \gamma_{RT} = 0.$

If this zero effect hypothesis is rejected, the parameters γ_{LR}, γ_{KR}, $\gamma_{F_{\ell s}R}$, and $\gamma_{F_{hs}R}$ appearing in (11), (12), and (16) will reveal the factor-using/factor-saving nature of environmental regulations. The interpretation of these parameters is seen most clearly from the cost share equations (12). Each parameter represents the partial derivative of the corresponding input cost share with respect to the regulatory intensity variable. Holding input prices, output, and time constant, the parameter takes a non-zero value only if regulation induces a change in input mix. A positive (negative) value for γ_{iR} implies that environmental regulations are ith-factor using (saving).

The relevant neutrality hypothesis is

(20) $\gamma_{LR} = \gamma_{KR} = \gamma_{F_{\ell s}R} = 0.$

If this hypothesis is rejected, environmental regulations bias the utility's input mix. The parameters $\gamma_{F_{\ell s}R}$ and $\gamma_{F_{hs}R}$ are of particular interest. The expectation is that $\gamma_{F_{\ell s}R}$ will be positive and $\gamma_{F_{hs}R}$ will be negative; environmental regulations are low-sulfur fuel using and high-sulfur fuel saving. The important empirical issue is the extent of this fuel shift effect on productivity growth.

Technical change. The basic technical change hypothesis is $v_T = 0$ or, from (15),

(21) $\beta_T = \gamma_{LT} = \gamma_{KT} = \gamma_{F_{\ell s}T} = \gamma_{QT} = \gamma_{RT} = \gamma_{TT} = 0.$

If this is rejected, the most interesting technical change hypothesis for the electric power industry concerns the impact of changing factor prices, especially fuel prices, on the rate of technical change. Changing input prices affect the least cost combination of inputs and therefore can affect the rate of technical change. If, for example, technical change is capital-using, an increase in the price of capital not only encourages substitution of other inputs for capital but also makes the adoption of the capital-using innovations more costly. The result is a lower rate of cost reduction associated with technical change. If, however, technical change is capital-saving, an increase in the price of capital has just the opposite effect on the rate of technical change. Substitution is still encouraged but now toward an input combination consistent with the capital-saving nature of technical change. Adopting the innovation, by economizing on a now more expensive input, increases the rate of cost reduction associated with technical change. The ultimate effect on technical change is a function of substitution possibilities and the factor-using/factor-saving nature of technical change.

The direction and magnitude of these price effects depend on the estimates of the parameters γ_{LT}, γ_{KT}, $\gamma_{F_{\ell s}T}$, and $\gamma_{F_{hs}T}$ appearing in (15). Each represents the logarithmic partial derivative of the rate of cost reduction due to technical change with respect to the corresponding input price, $\partial(\partial \ell nC/\partial T)/\partial p_i$. If γ_{iT} is positive (negative), technical change is ith-factor-using (saving), implying that relative price increases in the ith input reduce (increase) the rate of technical change. If the parameter equals zero, technical change is ith-factor-neutral, implying that price changes for the ith input have no effect on technical change. Hicks-neutral technical change is implied by

$$(22) \quad \gamma_{LT} = \gamma_{KT} = \gamma_{F_{\ell s}T} = 0.$$

Should this be rejected, most interest focuses on the fuel bias parameters $\gamma_{F_{\ell s}T}$ and $\gamma_{F_{hs}T}$.

The results of all hypothesis tests as well as the decomposition of a representative utility's productivity growth v_G into its source components (9) are reported in section 4.

3. The Data

All production, market, and regulatory data developed for this research relate specifically to fossil-fueled generation. If emission standards affect productivity growth in the electric power industry, they are expected to affect the productivity of fossil-fueled production, the precise target of environmental regulation. Consequently, this study abstracts from all transmission and distribution activity as well as all nuclear and hydroelectric generating capacity.

The estimating model requires utility data on generation cost, input expenditures, output, input prices, and environmental regulations. The necessary data are available for the 1973-79 period for 56 privately-owned utilities. These firms vary both in size and in the stringency of environmental standards, thereby enabling us to contrast the productivity contributions of scale economies, environmental regulation, and technical change. The analysis begins with 1973 since detailed fuel transaction data, including sulfur content by transaction, are first reported in that year; 1979 is the most recent year for which all necessary data are available. The sample years not only span the period when environmental regulations became increasingly important but also represent a complete business cycle.

Output, Inputs, and Input Prices. Annual output for each utility is measured as net steam generation (KWH) reported in the annual editions of Statistics of Privately Owned Electric Utilities in the United States (hereafter, Statistics).

Total expenditures for labor input are defined as the sum of production payroll for steam generation (P_{SG}) plus pensions and benefits accruing to those laborers (B_{SG}). Neither expenditure component is reported directly. Under the assumptions that all generation employees within a utility receive identical wages and that firm benefits are distributed in proportion to payrolls, P_{SG} and B_{SG} are calculated as follows:

$$P_{SG} = P_T \frac{L_S}{(L_S+L_H+L_N)} \qquad B_{SG} = B_T \left(\frac{P_{SG}}{P_T}\right) ,$$

where P_T and B_T, respectively, are total utility payroll and benefits reported in Statistics and L_S, L_H, and L_N represent the number of utility steam, hydro-electric, and nuclear employees, respectively, reported in Steam-Electric Plant Construction Cost and Annual Production Expenses and Hydroelectric Plant Construction Cost and Annual Production Expenses.[22]

The price of labor input in each utility is measured as the average annual labor expenditure per steam generation employee:

$$P_L = (P_{SG} + B_{SG})/L_S.$$

It is important to note that by including pensions and benefits, P_L measures the full cost of a steam generation employee to the utility.

The measures of utility expenditures for capital input and capital's service price are constructed according to methods originally described in Christensen and Jorgenson (1969). Expenditures are defined as the product of the capital stock of steam production plant (K) and its service price (p_K). The capital stock in each period is constructed according to the perpetual inventory method of capital accumulation.[23] Steam production plant investment data reported for the 1950-1979 period in Statistics are converted to real stock additions by the use of 1966 acquisition prices extrapolated over 1950-1979 using the Handy-Whitman Index of Utility Construction Costs. Capital decay for each asset type is assumed to follow the 1.5 declining balance pattern;[24] the service life of 33 years is determined from engineering estimates.[25] The service price p_K is constructed according to the definitions applied in Christensen, Gollop, and Stevenson (1980). It is a marginal price, a function of capital gains, the service life of the asset, tax policy, and the firm's opportunity cost of capital.

Fuel expenditure and fuel price data for both low-sulfur and high-sulfur fuels are constructed from transaction-specific data found in the Monthly Report of Cost and Quality of Fuels for Electric Plants (hereafter, Monthly Report). Among other information, the Monthly Report records the fuel type, physical quantity, BTU content, delivered cost, and sulfur content of each fuel transaction at each electric plant. Once a sulfur-content boundary distinguishing low-sulfur and high-sulfur fuels is established, each transaction can be assigned to the appropriate low-sulfur or high-sulfur category. Each utility's expenditures for low-sulfur (high-sulfur) fuels are defined as the sum over all transactions of the delivered cost of low-sulfur (high-sulfur) fuels purchased by any of its plants.[26] The corresponding price per million BTUs is defined as the ratio of total low-sulfur (high-sulfur) fuel expenditures to the quantity of low-sulfur (high-sulfur) fuel purchased, stated in BTUs.

Consultations with staff personnel in the Department of Energy's Office of Coal and Electric Utility Statistics and the Policy Planning Division of the Environmental Protection Agency suggested that fuels which produce more than 1.5 pounds of sulphur dioxide per million BTUs when burned be classified as high sulfur.[27] Fuels below this boundary are classified as low sulfur.[28]

Regulatory Intensity. The final data series involves the measure of regulatory intensity, R. Modeling R as a dummy variable taking the unit value when an emission standard exists and zero otherwise is inadequate because the severity of environmental regulations varies considerably over time and across firms. While an improvement, measuring R solely in terms of the legal emission standard is still deficient because it fails to account for permitted variances, a firm's simple failure to comply with the standard, and, most importantly, the extent to which the standard actually constrains the utility. What affects producer behavior, and therefore cost and productivity, is the firm's perception of the stringency of the standard for its particular operation. An appropriate measure of R must reflect the shadow price of environmental regulation as perceived by each utility.

This research defines R for each utility as a function of the legal emission standard, the effective enforcement imposed on the utility, and the extent to which actual emission rates deviate from unconstrained emission rates. At year t

$$(23) \qquad R_t \equiv \left(\frac{E_t^* - S_t}{E_t^*} \right) \left(\sum_{i=t-1}^{t} \tfrac{1}{2} \frac{E_t^* - E_i}{E_i^* - S_i} \right),$$

where S_t, E_t and E_t^* are all expressed as emission rates (lbs of SO_2/MBTU) and are, respectively, the legal standard constructed from the relevant State Implementation Plan (SIP), the utility's actual emission rate, and the utility's desired or unconstrained emission rate.

The first term in (23) is the proportional reduction in unconstrained emissions required by the SIP and captures the extent to which the legally allowed emission rate constrains the firm. It has an upper bound of unity which would occur if the SIP mandated no emissions ($S_t = 0$). In practice this upper bound is never reached. The ratio is bounded from below by zero. This occurs whenever the legal standard is greater than or equal to the firm's unconstrained emission rate ($S_t \geq E_t^*$), implying that the standard is of no importance to the firm.[29]

The second term in (23) serves as an enforcement scalar and reflects the degree to which a firm's actual emission reduction corresponds to the required emission reduction. Under the assumption that actual emission rates, for firms which face legal standards, are reasonable indicators of the emission rates actually permitted by state enforcement agencies, enforcement is defined as a two year moving average of the ratio of the actual reduction to the legally required reduction in emission rates.[30] The enforcement scalar also is bounded in the zero-one interval. It is set equal to unity anytime

$E_t < S_t$, the actual emission rate is less than the legal standard, to reflect complete enforcement of the standard. It is bounded from below by zero whenever the actual emission rate equals the unconstrained emission rate ($E_t = E_t^*$).[31]

Each of the two components of R is measured and bounded before being multiplied together. Consequently, the regulatory intensity variable R is bounded between zero and unity.

The legal emission limit, S_t, is constructed at the plant level using the SIP for the relevant state and the EPA publication State Implementation Plan Emission Regulations for Sulphur Oxides: Fuel Combustion, Second Edition.[32] Conversations with staff at state environmental protection agencies were used to verify the relevant state laws and resolve discrepancies between sources. In order to construct the firm standard, plant standards are aggregated using the plants' share in total firm BTUs as weights.

The firm's actual emission rate, E_t, is calculated using the plant fuel transaction data reported in Monthly Report. The sulfur and BTU contents of each fuel transaction are used to construct total sulfur emissions and total BTU use for each plant using conversion formulas in Steam Electric Plant Air and Water Quality Control Data, 1969. Sulfur emissions are reduced for plants with installed scrubber systems. These adjustments are based on the design efficiency of the scrubbers and the proportion of plant capacity on which the scrubber is installed.[33] Finally, the plant totals are summed to the firm level and a firm level emission rate is constructed.

The firm's desired or unconstrained emission rate, E_t^*, is calculated using the sulfur and BTU contents of all its fuel purchases in the high-sulfur fuel category. It is the average emission rate for all fuel purchases which would result in emission rates greater than 1.5 pounds of SO_2/MBTU.[34]

The main advantage of this measure is that it acknowledges that utilities, even if unconstrained by environmental regulations, still would purchase fuels with differing sulfur contents. Based on the actual mix of high sulfur fuels purchased by the utility, E_t^* recognizes that the firm normally would adjust its unconstrained purchases in response to changing sulfur premiums, transportation rates, and supply constraints. The main disadvantage of E_t^* is that it results in a conservative estimate of the regulatory intensity variable in the later years of the sample because it does not attribute any of the reduction in the average emission rate of the high-sulfur fuel category to regulation. This average high-sulfur fuel emission rate has fallen in our sample from a high of 4.18 lbs. of SO_2/MBTU in 1974 to a low of 3.78 lbs. of SO_2/MBTU in 1979.[35]

Overall, the regulatory intensity variable attempts to measure the severity or importance of emission constraints on utility operations. Only when firm actions have been affected by regulation do we expect to see regulation-induced effects on the rate of productivity growth. The regulatory intensity variable is introduced into the cost function to capture these effects.

Estimating Model. The estimating model consists of the cost function (11) and the four factor share equations (12). Symmetry and linear homogeneity restrictions are imposed. Fraumeni and Jorgenson (1982) recently have implemented a procedure, originally developed by Lau (1978), to insure that the estimated cost function is concave in factor prices for all prices which would result in non-negative factor cost shares. We use their procedure, which is based on the Cholesky factorization of the matrix of second-order price parameters from the translog function, to insure concavity of the estimated cost function.

The stochastic disturbances in the estimating equations for any observation are assumed to be correlated across equations. Iterative-Zellner estimation is used after one share equation is deleted to avoid singularity of the estimated variance-covariance matrix across equations. The resulting estimates are maximum likelihood. All hypothesis tests are evaluated using the likelihood ratio test statistic.[36]

4. Empirical Results

Parameter estimates for the translog cost function are reported in Table 1. These were estimated subject to symmetry, linear homogeneity, and concavity restrictions and provide the basis for all hypothesis tests summarized in Table 2. Measures of scale economies, technical change, and the cost effect of environmental regulation also depend on the cost function parameters. Each of these productivity determinants is discussed in a separate subsection. Together, they are instrumental in the source decomposition of productivity growth, the topic of the closing subsection.

Regulation. The impact of changes in regulatory intensity on cost, v_R, is defined in (14). The seven restrictions identified in (19) maintain $v_R = 0$. As reported in Table 2, this "zero effect" hypothesis is rejected at the .01 significance level.[37] The estimates of v_R not only are non-zero but also have the expected sign. Average annual values of v_R reported in Table 3 are positive in every year. Moreover, except for 1978, the estimates increase steadily from a low of .119 in 1973 to a high of .371 in 1979, implying that a given increase in the intensity of regulation has become more costly over time.[38]

The estimates of v_R can be converted to elasticity form by multiplying $\hat{v}_R$ at each observation by the corresponding value of R. The average annual estimates of these elasticities vary from a low of .051 in 1973 to a high

Table 1

Cost Function Parameter Estimates
(standard errors in parentheses)

Parameter	Estimate	Parameter	Estimate
β_0	11.9980 (.0314)	γ_{LQ}	-.0082 (.0172)
β_L	.0819 (.0335)	γ_{KQ}	-.0224 (.0050)
β_K	.3676 (.0111)	$\gamma_{F_{\ell s}Q}$	.0358 (.0076)
$\beta_{F_{\ell s}}$	.1225 (.0169)	$\gamma_{F_{hs}Q}$	-.0052 (.0082)
$\beta_{F_{hs}}$	.4280 (.0181)	γ_{QQ}	.0412 (.0151)
β_Q	.9817 (.0196)	γ_{QR}	.1389 (.0469)
β_R	.1783 (.1442)	γ_{QT}	-.0105 (.0038)
β_T	.0537 (.0169)	γ_{LR}	.0331 (.0846)
γ_{LL}	-.0001 (.0002)	γ_{KR}	-.0653 (.0249)
γ_{LK}	-.0002 (.0101)	$\gamma_{F_{\ell s}R}$	.6128 (.0382)
$\gamma_{LF_{\ell s}}$	.0028 (.0047)	$\gamma_{F_{hs}R}$	-.5806 (.0415)
$\gamma_{LF_{hs}}$	-.0025 (.0117)	γ_{RR}	.7917 (.3511)
γ_{KK}	-.0009 (.0017)	γ_{RT}	.0136 (.0190)
$\gamma_{KF_{\ell s}}$	.0115 (.0106)	γ_{LT}	-.0029 (.0082)
$\gamma_{KF_{hs}}$	-.0104 (.0088)	γ_{KT}	-.0131 (.0024)
$\gamma_{F_{\ell s}F_{\ell s}}$	-.1412 (.0212)	$\gamma_{F_{\ell s}T}$	.0054 (.0037)
$\gamma_{F_{\ell s}F_{hs}}$	.1269 (.0204)	$\gamma_{F_{hs}T}$	.0106 (.0039)
$\gamma_{F_{hs}F_{hs}}$	-.1140 (.0212)	γ_{TT}	-.0120 (.0041)

Table 2

Test Statistics for Hypothesis Tests

Hypothesis	Equation Reference	Test Statistic	χ^2 Critical Value (α=.01)
Regulation:			
No regulatory effect (v_R=0)	(19)	299.65	18.48
No input bias	(20)	225.44	11.35
Scale:			
Constant Returns (v_Q=1)	(17)	138.57	18.48
Homogeneity	(18)	108.43	16.81
Technical Change:			
No technical change (v_T=0)	(21)	61.86	18.48
Hicks neutrality	(22)	38.89	11.35

Table 3

Estimated Partial Effects of Regulation, Scale, and Time on Cost
(mean values over all firms)

Year	v_R	v_Q	$-v_T$
1973	.119	.943	.037
1974	.206	.951	.034
1975	.233	.945	.023
1976	.265	.941	.011
1977	.327	.938	.001
1978	.296	.927	-.011
1979	.371	.918	-.026

of .098 in 1979. On average, a one percent increase in R during 1979 would have resulted in a .098 percent increase in total generating cost. If the analysis is restricted to firms which had non-zero values for the regulatory intensity variable, the average yearly cost elasticities vary from a low of .089 in 1975 to a high of .134 in 1979. In dollar terms, a one percent increase in regulatory intensity in 1979 would have rasied the average level of total cost for firms which faced effective regulation by 478 thousand dollars. The average cost per million KWH would have risen by 41 dollars.[39]

This regulatory cost effect is due primarily to the input biasing character of environmental regulations. The argument leading to this conclusion begins with the input-neutrality restrictions (20). The "no input bias" test statistic reported in Table 2 is significant at the .01 level. The fuel input bias parameter estimates $\hat{\gamma}_{F_{hs}R}$ and $\hat{\gamma}_{F_{\ell s}R}$ presented in Table 1 suggest environmental regulation is low-sulfur using and high-sulfur fuel saving. Both effects are statistically significant. In addition, the parameter estimates $\hat{\gamma}_{KR}$ and $\hat{\gamma}_{LR}$ indicate that regulation has had a positive but insignificant effect on the cost share of labor and a significant negative effect on the cost share of capital.

Though the γ_{iR} coefficients are sufficient to test for the existence of input bias, they, by themselves, cannot determine the direction of input bias. These parameters indicate only the sensitivity of cost shares to changing regulatory intensity. The actual direction and magnitude of input bias depend on how demand for each input responds to changes in the regulatory environment.

Using the definition of the cost share, the demand for the ith input can be expressed as

$$(24) \qquad X_i = \frac{C}{P_i} v_i,$$

where C and v_i are defined in (11) and (12), respectively. Logarithmically differentiating (24) with respect to R produces the following expression in terms of the translog parameters

$$(25) \qquad \frac{\partial \ln X_i}{\partial \ln R} = R(v_R + \frac{\gamma_{iR}}{v_i}) \qquad (i = L, K, F_{\ell s}, F_{hs}).$$

The direction of input bias depends on the relative magnitudes of the overall cost effect v_R and the share weighted bias parameter. The mean values of these elasticities over the complete sample are .126, .037, .493 and -.551 for labor, capital, low-sulfur fuel, and high-sulfur fuel, respectively. Environmental regulations have increased the representative electric utility's demand for labor, capital, and low-sulfur fuel. Not surprisingly, the demand for high-sulfur fuel has declined.

It is important to note that while regulation has reduced the cost share of capital ($\gamma_{KR}<0$), it has increased the demand for capital ($\partial \ln K/\partial \ln R>0$). This latter derivative is positive in every sample year. It also increases each year from a low of .022 in 1973 to a high of .064 in 1979. This trend is consistent with the fact that the use of exhaust gas scrubbers became more common over this period.

The last step in the argument regarding the importance of input bias relies on the definition of total cost, $C = \Sigma p_i X_i$. It follows that

$$(26) \qquad \frac{\partial C}{\partial R} = \Sigma p_i \frac{\partial X_i}{\partial R}$$

or, using (25),

$$(27) \qquad \frac{\partial \ln C}{\partial \ln R} = \Sigma \frac{p_i X_i}{C} \frac{\partial \ln X_i}{\partial \ln R} = \Sigma v_i \left(v_R + \frac{\gamma_{iR}}{v_i}\right) R.$$

Using the cost function parameter estimates, the average values of the input specific components of (27) are .010, .010, -.056, and .103 for labor, capital, high-sulfur fuel, and low-sulfur fuel, respectively. Clearly, the cost effect of environmental regulations has resulted primarily from input bias, particularly from regulation-induced switching from lower priced high-sulfur to higher priced low-sulfur fuels.

Scale. The important scale hypotheses are constant returns to scale and homogeneity. The test statistics for these hypotheses are reported in Table 2. Each is significant at the .01 level. Given the definition of the scale effect in (9), the rejection of constant returns indicates that output growth will be an important determinant of productivity growth. The absence of homogeneity additionally implies that productivity growth will be a function of firm size as well as output growth.

Mean annual average estimates of the elasticity of cost with respect to output are reported in Table 3. The estimates of v_Q indicate that the average utility in each year 1973-79 operated in a region of scale economies, $\hat{v}_Q < 1$. The cost elasticity in any year varies from approximately .82 to 1.07, implying that the smallest firms still faced substantial scale economies while the largest sample firms were producing in a region of scale diseconomies.[40]

The input bias parameters γ_{iQ} reported in Table 1 provide additional insights into how scale affects productivity growth. Of particular interest are the parameters for low and high-sulfur fuels. The impact of increased output on the share of high-sulfur fuel, $\hat{\gamma}_{F_{hs}Q}$, is negative but not statistically significant. However, $\hat{\gamma}_{F_{\ell s}Q}$, the effect of increased output on the share of low-sulfur fuel, is positive and significant. This is consistent with the observation that larger generating units generally face more strict emission standards and therefore have larger demands for low-sulfur fuels than smaller generating units.

This inference is supported further by the statistically significant estimate of γ_{QR} reported in Table 1. Inserting this positive coefficient into the definition of scale economies, equation (13), reveals that increased regulatory intensity reduces the level of scale economies or, equivalently, reduces the cost benefits of larger scale operations.

Improvements in technology during the 1970s partially offset the adverse scale effects of environmental regulations. The parameter estimate $\hat{\gamma}_{QT}$ is negative and significant, suggesting that, holding output, regulation, and factor prices constant, technical change has increased the degree of scale economies during the 1970s.[41] In fact, technical change is largely responsible for the improvement in scale economies observed in Table 3 for the 1973-79 period.

Technical Change. Test statistics for the hypotheses of no technical change and Hick's neutral technical change are reported in Table 2. Both hypotheses are rejected at the .01 significance level. The factor using/factor saving nature of technical change is summarized in the γ_{it} parameter estimates reported in Table 1. The estimates reveal that technical change is fuel using and capital and labor saving.[42] This implies that rising fuel prices in the 1970s reduced the rate of technical change.

The expected pattern emerges in the average yearly estimates of the rate of technical change reported in Table 3. As utilities adjusted to rising fuel prices, the estimates $\hat{v}_T$ reveal a strong upward trend from a low value of -3.7 percent per year in 1973 to a high of 2.6 percent per year in 1979; $\hat{\gamma}_{TT}$ is negative and statistically significant. Over the years 1973-77, technical regression resulted in reduced rates of productivity growth. Technical change acted as a positive source of productivity growth for the years 1978 and 1979.

Sources of Productivity Growth. The rate of productivity growth, defined as the negative of the growth in average cost holding input prices constant, is defined in continuous time using the translog parameters in (16). Before the sources of growth can be calculated, a discrete time counterpart to (16) must be developed.

Using Diewert's (1976) quadratic approximation lemma, a discrete time Tornqvist index of productivity growth is defined from (9) as the average rate of productivity growth between two points in time, (T-1) and T: [43]

$$(28) \qquad \bar{v}_G \equiv (1-\bar{v}_Q)\Big(\ell nQ(T)-\ell nQ(T-1)\Big) - \bar{v}_R\Big(R(T)-R(T-1)\Big) + \bar{v}_T,$$

where

$$\bar{v}_Q \equiv \tfrac{1}{2}\Big(v_Q(T) + v_Q(T-1)\Big)$$

$$\bar{v}_R \equiv \tfrac{1}{2}\Big(v_R(T) + v_R(T-1)\Big)$$

$$\bar{v}_T \equiv \tfrac{1}{2}\Big(v_T(T) + v_T(T-1)\Big).$$

It is important to note that the scale effect is a function of scale economies and market growth and that the regulatory effect is a function of the partial cost impact of regulation $\bar{v}_R$ and the change in regulatory intensity.

Estimates of the average annual sources of productivity growth are reported in Table 4. They are calculated separately for firms which faced binding sulfur dioxide emission constraints ($R \neq 0$) in at least one of the two years over which the average is calculated and for firms which did not face effective emission restrictions ($R=0$) in either year. Three descriptive statistics are worthy of note. The number of firms whose emissions were constrained by regulations increased from 24 to 41 over the sample period. Fifteen of the sample firms were not effectively constrained by sulfur dioxide regulations in 1979; eleven of these were never constrained during the complete sample period.

Table 4

Sources of Productivity Growth:
Average Annual Rates of Growth
(means over all firms)

Period	Number of firms	Productivity Growth $\bar{v}_G$	Regulation $-\bar{v}_R \cdot (R(T)-R(T-1))$	Scale $(1-\bar{v}_Q) \cdot (\ln Q(T) - \ln Q(T-1))$	Technical Change $\bar{v}_T$
Firms Facing Binding Emission Constraints:					
1973-74	24	-.0327	.0050	-.0002	-.0375
1974-75	36	-.0295	-.0038	.0024	-.0282
1975-76	39	-.0271	-.0196	.0088	-.0164
1976-77	39	-.0072	-.0063	.0041	-.0051
1977-78	38	.0017	-.0054	.0011	.0060
1978-79	41	.0139	-.0055	.0010	.0183
Average		-.0135	-.0059	.0029	-.0105
Firms Not Facing Binding Emission Constraints:					
1973-74	32	-.0348	0	-.0011	-.0337
1974-75	20	-.0297	0	-.0008	-.0289
1975-76	17	-.0134	0	.0057	-.0191
1976-77	17	-.0090	0	-.0008	-.0083
1977-78	18	.0076	0	.0039	.0036
1978-79	15	.0273	0	.0083	.0190
Average		-.0087	0	.0025	-.0112

The overall trend in productivity growth is similar for both groups of firms. Negative rates of productivity growth of more than 3 percent per year at the beginning of the sample period increase steadily and become positive after 1977. However, the average annual rate of productivity growth over the 1973-79 period for the constrained firms is -1.35 percent, which is almost half a percentage point lower than the -.87 percent average rate for the unconstrained firms.

Most of the difference occurs over the 1975-79 period. For those years the constrained firms have an average annual productivity growth rate of -.46 percent compared to .31 percent for the unregulated firms. The reason for this large difference can be seen by examining the separate productivity contributions of regulation, scale, and technical change.

The contribution of environmental regulation to productivity growth is summarized in Table 4. On average, it reduced the annual rate of productivity growth for regulated firms by .59 percentage points. After 1975, this annual average reduction increases to .88 percentage points. The largest impact of regulation occurs in 1976, the first full year in which the EPA's ambient air quality standards were supposed to be met. During that year, productivity growth fell by almost two percentage points as a result of increased regulatory intensity. Since then the yearly regulatory impact has been much smaller, varying from -.54 to -.63 percentage points. The overall conclusion is clear. In recent years, environmental regulation has resulted in a .5 to .6 percentage point decline in the annual rate of productivity growth for constrained firms in the electric utility industry.

Scale economies in production have not played a large role as a contributing source of productivity growth over this period for either group of firms. In general this is due to the low rate of output growth over the period and not the exhaustion of scale economies in production. Average output growth rates during 1973-79 were 2.3 percent per year for constrained firms and 2.1 percent for unconstrained firms. On average, the scale contribution to productivity growth was less than .3 percentage points per year for both groups. Virtually all of the difference in the scale contribution between the two groups of firms for any year is due to differences in the rate of growth of output and not large differences in the degree of scale economies available to them. While there still may be unexploited economies of scale available to the average size firm in this industry, the contribution of scale effects to productivity growth will continue to be extremely small unless output growth rates increase significantly.

The importance of the final source of productivity growth, the shift in the cost function over time due to technical change, is summarized in the last column of Table 4. Like the scale contribution, annual rates of technical change do not differ greatly between the two groups of firms. On average, productivity growth has fallen by 1.05 percentage points per year for the constrained firms as a result of technical regression and 1.12 percentage points for the unconstrained firms. Note, however, that while the average contribution of technical change has been negative, the trend over time has been positive. Large negative rates of technical change in the early years of the sample fell in magnitude over time and became positive in the 1977-79 period. In fact, technical change is responsible for the observed upward trend in the rate of productivity growth. Importantly, positive rates of technical change in the 1977-79 period were sufficient to overcome the negative effect of environmental regulations in those years, thereby restoring positive productivity growth to the industry.

5. Conclusion

Environmental regulations popularly are blamed for the disappointing productivity performance of electric utilities in the seventies. In spite of this issue's provocative nature, little quantitative evidence has surfaced in the economics literature. We suspect this is due, in part, to the difficulty of transforming the notion of environmental regulation into a meaningful and measurable variable.

This paper attempts to fill this gap by introducing an index of regulatory intensity that is used to disentangle the competing determinants of the industry's performance during the 1973-79 business cycle. The shadow price variable R developed for this research is a function of the severity of the emission standard, the extent of enforcement, and the unconstrained emission rate relevant to each utility. The principal conclusion is that sulfur dioxide emission regulations have resulted in both significantly higher generating costs and markedly lower rates of productivity growth. Among utilities facing effective regulation, the elasticity of cost with respect to regulation rose from .089 in 1975 to .134 in 1979. The evidence makes clear that this cost impact results primarily from regulation-induced input bias, particularly an increased reliance on expensive low-sulfur fuels. For a representative utility in 1979, a one percent increase in regulatory intensity would have increased generating costs by 478 thousand dollars or by 41 dollars per million KWH.

The actual impact on industry performance is best viewed through the effect of emission regulations on productivity growth. Compared to unconstrained firms, the average rate of productivity growth for environmentally constrained utilities was reduced by .59 percentage points per year during

1973-79. Stated equivalently, annual average productivity growth in the industry would have been 44 percent higher had it not been for sulfur dioxide regulations. By raising the average yearly generating cost per million KWH by 122 dollars, this decline in productivity performance cost the average regulated utility and its ratepayers 1.35 million dollars each year.

The productivity effects were considerably larger over 1975-79, precisely the period (beginning July 1975) when utilities were to meet EPA ambient air standards. Environmental regulations reduced the annual productivity growth rate of constrained utilities by .88 percentage points. This more than accounted for the full difference in annual productivity growth rates of unconstrained and constrained utilities. The 1975-79 average rate of productivity growth for the former was .31 percent while for the latter it was -.46 percent.

Finally, it is important to note what we hope is obvious: Society presumably benefits from cleaner air. This paper should not be interpreted as an assault on the merits of environmental regulation. Rather, it is an attempt to identify the effects of emission constraints on average generating cost and productivity growth defined in terms of marketable output.

Notes

1. The Clean Air Act Amendments of 1970 modify the Clean Air Act of 1963 and the Air Quality Act of 1967. For the complete text of the 1970 amendments, see U.S. Code Annotated: Congressional and Administrative News (1971), pp. 1954-2001.

2. Denison (1978) argues that as much as .35 percentage points of the growth in total factor productivity in 1975 were lost due to environmental and safety regulation. See also Denison (1979) pp. 58-9, 65-71, and 111.

3. U.S. Federal Energy Regulatory Commission (1959f), p. XII; U.S. Federal Energy Regulatory Commission (1973f), p. XIX; U.S. Federal Energy Regulatory Commission (1977a), Table 3; and U.S. Federal Energy Regulatory Commission (1980a), Table 3.

4. Stevenson (1980), Gollop and Roberts (1981), and Fraumeni and Jorgenson (1982) find that the technology in the electric power industry is fuel-using.

5. U.S. Federal Energy Regulatory Commission (1959b, 1973b), Table 23 and U.S. Federal Energy Regulatory Commission (1980b), Table 31.

6. See Christensen and Greene (1976) and Gollop and Roberts (1981) for a description of scale economies in electric utilities.

7. Fraumeni and Jorgenson (1980), Table 23 and unpublished series.

8. See Roberts and Farrell (1978) for a discussion of the SIP process and its effectiveness.

9. See Randle p. 1722.

10. The development of these 1978 new source standards and their impact on utilities is detailed in Ackerman and Hassler (1980).

11. A detailed case study of how six utilities have responded to environmental restrictions is presented in Roberts and Bluhm (1981).

12. U.S. Federal Energy Regulatory Commission (1980a), Table 15. In addition, 66 percent of the total number of barrels of oil purchased was low-sulfur oil.

13. U.S. Federal Energy Regulatory Commission (1975a,1980a).

14. The EPA decisions on these questions have been upheld in court. For a discussion of the legal implications of the Clean Air Amendments on electric utilities see Raffle (1978) and Randle (1979).

15. Though productivity studies commonly are characterized in terms of the production function, duality theory stresses the correspondence between production and cost functions; either can form the basis for a productivity study. For discussions of duality theory, see Diewert (1974) and Varian (1978) pp. 118-35.

16. Intermediate inputs other than fuel are relatively unimportant in the industry's production process and therefore are excluded from the analysis.

17. Regulatory intensity equals zero when the utility is not constrained by an emission standard. Consequently, derivatives involving R are stated in semi-logarithmic form.

18. As discussed below, the regulatory intensity variable R takes a zero value in the absence of any mandated emission standard. Consequently, like the time variable T in (11), R is not expressed in logarithmic form. Stated precisely, the translog cost function (11) is a discrete approximation to the implicit cost function $C\,(p_L, p_K, p_{F_{\ell s}}, p_{F_{hs}}, Q, e^R, e^T)$.

19. The cost function must be linear homogeneous in input prices. The estimated translog cost function will satisfy this condition at all data points if and only if

$$\sum_i \beta_i = 1$$

and $\sum_j \gamma_{ij} = \sum_j \gamma_{jQ} = \sum_j \gamma_{jR} = \sum_j \gamma_{jT} = 0 \qquad (i,j = L,K,F_{\ell s}, F_{hs}).$

20. Given $\gamma_{LQ} = \gamma_{KQ} = \gamma_{F_{\ell s}Q} = 0$, the linear homogeneity restrictions guarantee $\gamma_{F_{hs}Q} = 0$.

21. The linear homogeneity restrictions guarantee that $\gamma_{F_{hs}R} = 0$ whenever $\gamma_{LR} = \gamma_{KR} = \gamma_{F_{\ell s}R} = 0$.

22. Laborers in jointly owned plants are allocated to parent firms on the basis of each firm's plant ownership share.

23. Our measures of K and p_K are an extended subset of similar measures constructed by Christensen, Gollop, and Stevenson (1980) for each of 136 utilities in each year 1950-1975.

24. The decay pattern δ_K is defined by the 1.5 declining balance method; i.e., $\delta_K = 1.5/T_K$ where T_K is the service life of steam production plant.

25. The service life estimate for steam production plant was developed by engineers at the Wisconsin Public Service Commission.

26. Fuel purchased by jointly owned plants is allocated to the fuel accounts of parent firms on the basis of the parent firms' ownership shares.

27. This corresponds to a sulfur content of approximately .70 to 1 percent by weight for coal and 1.25 to 1.4 percent for oil. The exact conversion depends on the BTU content of the fuel. Conversion formulas are given in U.S. Federal Energy Regulatory Commission (1969e).

28. In order to judge the sensitivity of the results to this assumption, all estimation and hypothesis testing is carried out using fuel expenditure and price data based on sulfur boundaries of 1.2 and 1.8 as well as the 1.5 lbs. of SO_2/MBTU level.

29. Given our measure of the unconstrained emission rate, described below, 11 of the 56 sample firms never face an effective emission standard during the 1973-1979 period. This usually occurs in states which did not have serious air pollution problems and therefore did not build strict emission limits into their SIP.

30. The two year average recognizes that the firm cannot tell at each point in time whether or not it will be allowed to violate the emission standard. Instead it looks to recent past experience to establish perceived enforcement levels. Violations of the SIP standards can occur for many reasons including delays and extensions granted the utility in order to allow it to phase in regulations slowly, legal disputes over the SIP standards, or poor enforcement. In any of these cases the enforcement component of (23) will scale down the value of the regulation variable to recognize that the regulation constraint on the firm is less than that implied by the SIP.

31. Given our definition of the unconstrained emission rate (see below), E_t cannot be greater than E_t^*.

32. The most recent version of each SIP is published in The Environment Reporter - State Air Laws.

33. Design efficiencies for scrubbers are listed in U.S. Federal Energy Regulatory Commission (1980a). Actual operating efficiencies are not available. In our sample 15 firms had scrubbers installed on at least part of one plant for at least one year. However, with the exception of four firms, scrubbers do not play a large role in reducing firm level emissions in our sample.

34. When the estimation and hypothesis tests are repeated using 1.2 and 1.8 pounds of SO_2/MBTU as the dividing line between low and high-sulfur fuels, the unconstrained emission rate and regulatory intensity variable are recalculated using the new boundaries.

35. Two alternatives for the unconstrained emission rate are possible but are less desirable. One method would be to use the emission rate for the least expensive fuel type purchased by the firm. This assumes the unconstrained firm would purchase all one type of fuel. This ignores supply constraints and violates the observation that unconstrained firms buy a mix of different fuels. A second alternative is to use emission rates from a pre-regulation period such as 1970. This fails to account for changes in the market for fuel including changes in relative fuel prices and the establishment of new supply sources which would affect an unconstrained firm's fuel choice and thus its emission rate.

36. See the references in Christensen and Greene (1976) for further discussion of the estimation method and test statistic.

37. The results of all hypothesis tests concerning regulation, scale, and technical change remain unchanged when the dividing line between low and high-sulfur fuel is redefined as either 1.2 or 1.8 lbs. of SO_2/MBTU.

38. Virtually all of the movement in v_R from 1977 to 1979 is due to a decline in the average price of low-sulfur fuel between 1977 and 1978 followed by a large increase from 1978 to 1979.

39. The average level of total cost in 1979 for all firms which faced effective regulation was 358.05 million dollars in our sample. The average output level for these firms was 11.65 billion KWH.

40. The estimates of scale economies, particularly for the early years of our sample, are very similar to those found by Christensen and Greene (1976) using 1970 data.

41. Stevenson (1980) has found a similar scale bias due to technical change for the period 1964 to 1972.

42. Stevenson (1980), Gollop and Roberts (1981), and Fraumeni and Jorgenson (1982) all report the same pattern of technical change biases.

43. See Gollop and Roberts (1981), pp. 112-113 and 139 for a more detailed derivation using a model without regulatory effects.

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