Energy Price Changes and the Induced Revaluation of Durable Capital in U.S. Manufacturing

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I. INTRODUCTION

The measurement of long-lived durable capital stocks has occupied the attention of economists and growth accountants for decades. One indisputable fact is that physical-engineering and economic notions of capital are often different. For example, much industrial equipment of earlier vintages in existence today may still be able to operate smoothly and technically efficiently, yet its economic value may have dropped sharply since 1973 due to increased operating costs brought about by OPEC-induced energy price increases. The rate of economic depreciation of durable capital since 1973 is likely to be different from the rate of physical deterioration; the empirical issue of interest is how such energy price-induced economic depreciation can be measured.

When severe economic changes occur, however, even the traditional economic measures become less credible. For example, economic measures of capital stock are typically based either on the assumption that physical deterioration and economic depreciation occur at a constant geometric rate (the "net capital stock" procedure), or else that capital deterioration follows a "one-hoss shay" pattern with a constant Winfrey mortality probability distribution (the "gross capital stock" procedure). Neither of these traditional economic capital stock measurement procedures are able to incorporate the substantial economic depreciation possibly induced by the post-1973 energy price increases.

In this paper we attempt to obtain measures of capital stock that not only incorporate the <u>quantity</u> of capital, but also incorporate <u>quality</u>

changes, where capital quality depends on embodied energy efficiency and energy prices. In the analysis presented here economic depreciation will depend both on capital quantity and capital quality.

The paper proceeds as follows. In Section II we follow Berndt [1983] in linking the modern theory of cost and production with the quality or hedonic literature of Griliches [1972], Rosen [1974], Muellbauer [1975] and Triplett [1983]. According to this quality-quantity demand framework, if quality is important it must be evident in cost-minimizing factor quantity demand equations. As a corollary, input quality can be inferred indirectly using data on, among other things, input quantity. In this sense the existence of energy price-related capital quality is shown to be a testable empirical issue formulated within the modern theory of cost and production.

In Section III we develop and specify an empirically implementable quality-quantity factor demand model, in which the stock and quality of capital is fixed in the short run, capital quality depends on energy prices and the energy efficiency embodied in the surviving vintages of capital, and firms minimize variable costs in producing a given level of output.

In Section IV we outline data construction procedures and sources, and in particular develop a measure of the energy efficiency embodied in the capital stock quantity at time t that depends on the vintage structure of capital and the relative energy prices existing when earlier vintages of capital were originally purchased. Then in Section V, after discussing other data and econometric issues, we present empirical results for U.S. manufacturing, 1947-77. Here we include alternative estimates of quality-adjusted capital stocks, and compare these measures with those based on traditional energy price-independent capital stock measurement procedures.

Implications of these quality-adjusted capital stock measures for the magnitude of the alleged post-1973 productivity slowdown in U.S.

manufacturing are discussed in Section VI, while concluding remarks and suggestions for future research are presented in Section VII. Two data appendices are also included, Appendix A dealing with the construction of energy price series in U.S. manufacturing 1906-47, and Appendix B with the interpretation and measurement of energy price-dependent capital quality embodied in the physically surviving capital stock.

II. THE QUALITY-QUANTITY FACTOR DEMAND MODEL

A goal of the proposed research is to construct a quality-adjusted measure of the capital that accounts for varying energy efficiencies incorporated in the surviving vintages of previous investment. Unfortunately, there is a paucity of data directly measuring the vintage-specific energy efficiency of capital. Hence it will be necessary to construct a model that generates a framework for measuring such quality indirectly. Such a model is based on an integrated quality-quantity framework in the modern theory of cost and production.

Assume there exists a well-behaved, twice differentiable production function relating the flow of output y to the quantity flows of n strictly positive inputs, $x = [x_1, x_2,\ldots,x_n]$, a scalar index of quality for each of the n inputs, $b = [b_1, b_2,\ldots,b_n]$, and disembodied technical change as a function of time t,

$$y = F(x;b;t), \qquad (1)$$

where each scalar element of the vector b is specified to be a function of, for example, engineering design and performance variables, economic variables, and other relevant characteristics for each input (e.g., the educational attainment of workers), i.e.,

$$b_n = h_n(z_n), \qquad (2)$$

where b_n is the quality index associated with x_n and $z_n = [z_{n1}, z_{n2}, \ldots, z_{nk}]$ is the vector of associated quality characteristic measures. F is assumed to be homogeneous of degree one in x and monotonically increasing in b. Note that according to (1), the relationship among y and x depends on the quality of inputs b.

Given appropriate regularity conditions on F and with output quantity, input prices and quality fixed, dual to the production function (1) there exists a well-behaved cost function relating unit cost c = C/y to the vector of input prices $p = [p_1, p_2, \ldots, p_n]$, input quality, and technical change,

$$c = G(p;b;t). \qquad (3)$$

According to (3), minimum costs of producing output depend not only on the prices of inputs, but also on input quality.

The introduction of the quality vector b into the production and cost functions (2) and (3) is not new,[1] but merits attention and interpretation.

Following Lau [1982] and Berndt [1983b], we consider the special case where the vector b is restricted to $b = [1,1,\ldots,1,b_n]$, i.e. where quality changes affect only the nth input. For our empirical implementation, we will specify that x_n is the capital quantity input and that b_n is its quality. In this instance the production function (1) reduces to

$$y = F(x_1,x_2,\ldots,x_n,b_n,t). \tag{4}$$

To provide an economic interpretation of input quality consistent with the theory of cost and production, we first solve (4) to obtain an input requirement function for x_n corresponding to each level of b_n, i.e.

$$x_n = f(y,x_1,x_2,\ldots,x_{n-1},b_n,t). \tag{5}$$

The relative qualities of inputs is determined as follows. Suppose we have two different quality levels of x_n, denoted b_{n0} and b_{n1}. Let us compare the different required quantitities of x_n corresponding to these two quality levels:

$$\frac{x_{n0}}{x_{n1}} = \left[\frac{f(y,x_1,x_2,\ldots,x_{n-1},b_{n0},t)}{f(y,x_1,x_2,\ldots,x_{n-1},b_{n1},t)}\right] \tag{6}$$

As Lau has noted, x_{n0}/x_{n1} represents the conversion ratio between two different quality levels of the nth input. Note that this conversion ratio in (6) generally depends on y, x, and b.

Now let us obtain a measure of x_{n0} in terms of the quantity of x_{n1} having quality level b_{n1}. This can be interpreted as measuring capital quantity x_{n0} with say, energy or thermal efficiency design quality b_{n0} in terms of the capital quantity x_{n1} having a different energy efficiency design quality b_{n1}. The quantity of x_{n0} in terms of its equivalent quantity in x_{n1} units is given by rewriting (6) as

$$x^*_{n0} = \left[\frac{f(y,x_1,x_2,\ldots,x_{n-1},b_{n0},t)}{f(y,x_1,x_2,\ldots,x_{n-1},b_{n1},t)}\right] \cdot x_{n1} \tag{7}$$

Next consider the output y* that could be produced with these x^*_{n0} units having b_{n0} quality level, given by

$$y^* = F(x_1,x_2,\ldots,x^*_{n0},b_{n0},t), \tag{8}$$

and compare this y* with the output y' obtained by employing quantity level x_{n1} with quality level b_{n1},

$$y' = F(x_1,x_2,\ldots x_{n1},b_{n1},t). \tag{9}$$

Lau [1982, p. 177] has shown that these two outputs are precisely equal, i.e., y* = y'. What this important result means is that not only does one have a way of quality-adjusting an input in terms of a standard unit, but these quality-adjusted measures can also be substituted directly into a production or cost function defined in terms of the standard unit.[2]

In essence, therefore, the task performed by the conversion ratio (6) and the quality-adjustment expression (7) is to standardize the various capital qualities-quantities into a common unit of measurement. This implies that up to a factor of proportionality, the various quality-rated capital quantities x_n^* are constructed to be perfect substitutes for one another. Note, however, that the important proportionality factor b_n can vary with input quantities, prices, or other characteristics, and need not be constant.

Empirical implementation of this quality-quantity approach within the context of cost and production functions requires careful specification of the conversion functions (6) or the quality-adjustment measures in (7). We first consider the special case where the quality-adjustment factor in square brackets in (7) is specified to be independent of $y, x_1, x_2, \ldots x_{n-1}$ and depends only on t and on the engineering design characteristics in z. In such a case, as Lau has demonstrated, the ratio specification in (6) implies that the production function must assume the multiplicative factor augmentation form

$$y = F(x_1, x_2, \ldots, x_{n-1}, b_n \cdot x_n, t). \qquad (10)$$

Moreover, assuming cost minimization, the dual cost function in this case must have the form (see Lau [1982], pp. 180-182)

$$c = G(p_1, p_2, \ldots p_{n-1}, p_n/b_n, t). \qquad (11)$$

If improvements in, say, the energy performance characteristics of capital goods increase capital quality b_n, then in (10) the quantity of capital services x_n^* is augmented, while in (11) the capital service price is diminished. Note also that since the quality-adjusted quantity $x_n^* = b_n \cdot x_n$, while the quality-adjusted price $p_n^* = p_n/b_n$, i.e., price times quantity is invariant to quality measurement.

In the above example, the conversion ratio has been specified to be independent of $y, x_1, x_2, \ldots, x_{n-1}$ but dependent on t and the engineering design characteristics in z. A recent empirical implementation of such a model is found in Berndt [1983a]. A classic special case is the specification of Solow-neutral technical change in models of economic growth, where

$$K^*(t) = K(t)\, b_K(t) = K(t)\, e_K^{\lambda(t-t_0)} \tag{12}$$

i.e., where capital in quality-adjusted or augmented units K* at time t is written as capital in base period units K multiplied by an exponential function of time, where t_o is the base-period point in time and λ_k is the constant rate of factor augmentation for capital. In such a case the conversion ratio is a function only of time. Numerous other examples have occurred in the literature including, for example, quality adjustment of labor by educational attainment. Hence the empirical applicability of this conversion function is quite general.

Following Fisher-Shell [1968], Muellbauer [1975] calls the conversion specification under the assumption of independence from y and x the <u>simple repackaging hypothesis</u>; essentially, quality improvement here implies "more of the same." At the risk of confusing the nomenclature and for reasons that will soon become more obvious, we shall call this type of specification of quality conversion ratios the price-independent quality adjustment.

Under the price-independent quality adjustment specification, conversion ratios between two types of capital equipment, say an energy-efficient and an energy-inefficient model, are not permitted to depend on the price of energy. This is of course an unattractive situation, since it is useful to envisage energy price changes as affecting the quality of capital goods, and therefore their conversion ratios. For example, the relative quasi-rents accruing to equipment with varying energy efficiencies will generally change in response to energy price increases, and thus both asset and rental prices should also be affected.

Following Lau [1982] and Berndt [1983b], we therefore relax the assumption of price-independent quality adjustment by allowing the conversion function in (6) to be independent of $y, x_1, x_2, \ldots, x_{n-2}$, but a function of x_{n-1}, z_n, and t, where x_{n-1} is the quantity of energy. As will be seen, this has important implications.

When the conversion function (6) is independent of y and $x_1, x_2, \ldots, x_{n-2}$, the input requirement function must have the form[3]

$$x_n = f(y, x_1, x_2, \ldots, x_{n-1}, b_n, t) = f((y, x_1, x_2, \ldots, x_{n-1}, t) h_n(z_n, x_{n-1})) \quad (13)$$

which implies that the conversion function is of the form

$$\frac{x_{n0}}{x_{n1}} = \left[\frac{f(y, x_1, x_2, \ldots, x_{n-1}, b_{n0}, t)}{f(y, x_1, x_2, \ldots, x_{n-1}, b_{n1}, t)}\right] = \frac{h_{n0}(x_{n-1}, z_{n0})}{h_{n1}(x_{n-1}, z_{n1})} \quad (14)$$

and that the corresponding production function can again be written in multiplicative factor augmentation form as

$$\begin{aligned} y &= F(x_1, x_2, \ldots, x_{n-1}, b_n \cdot x_n, t) \quad (15)\\ &= F(x_1, x_2, \ldots, x_{n-1}, h_n(x_{n-1}, z_n) \cdot x_n, t). \end{aligned}$$

Moreover, the dual cost function to (15) can be shown to have the form

$$c = G(p_1, p_2, \ldots, p_{n-1}, p_n/h'(p_{n-1}, z_n), t). \tag{16}$$

Note that while in the production function (15) the augmentation factor b_n is a function of x_{n-1} and z_n, in the dual cost function (16) it is a function of p_{n-1} and z_n.[4] Since the value of the multiplicative factor augmentation or factor price diminution variable b_n in (16) depends on p_{n-1}, we call this more general specification <u>price-dependent quality adjustment</u>.[5]

Having expressed quality adjustment in terms of multiplicative factor quantity augmentation or factor price diminution functions, we now relate the quality conversion specification to the widely-used hedonic price equations. The traditional first order conditions from cost minimization or profit maximization imply that the prices of different (x_n, b_n) input bundles must be in proportion to their marginal productivities, i.e. at the margin the effective or quality-adjusted price per unit of the standardized quality must be equalized, so that

$$\frac{p_{n0}}{b_{n0}} = \frac{p_{n1}}{b_{n1}} = p_n^* \tag{17}$$

where p_n^* is a "base price" constant reflecting the price of the standardized quality-adjusted unit. This is the dual equivalent to the conversion ratio in (7). Taking logarithns of (17), we obtain the familiar hedonic price equation corresponding to price-independent quality adjustment,

$$\ell n\ p_n = \ell n\ p_n^* + \ell n\ b_n = \ell n\ p_n^* + \ell n\ h_n(z_n), \tag{18}$$

on to price-dependent quality adjustment

$$\ell n\ p_n = \ell n\ p_n^* + \ell n\ b_n = \ell n\ p_n^* + \ell n\ h_n(p_{n-1}, z_n). \qquad (19)$$

In (18), the quality unadjusted price of, say, capital $\ell n\ p_n$ is a log-log function of the quality-adjusted price of capital and the engineering or physical quality attributes z_n. It might be noted that estimates of hedonic equations similar to (18) for durable assets such as automobiles, trucks, and others have often appeared in the econometric literature; for a selecteed survey, see Griliches [1971]. Equation (19) is, however, more general in that it relates the quality-unadjusted price of capital not only to the quality-adjusted price and engineering characteristics of the capital equipment, but also to the price of energy, p_{n-1}.[6]

Once one specifies the form of the conversion function h_n, one can rewrite (19), solving for $\ln p_n^*$ in terms of $\ln p_n$ and $\ln h(p_{n-1}, z_n)$,

$$\ell n\ p_n^* = \ell n\ p_n - \ell n\ b_n = \ell n\ p_n - \ell n\ h_n(p_{n-1}, z_n), \qquad (20)$$

exponentiate p_n^*, and then insert (20) into the standardized or quality-adjusted cost function (16). Cost-minimizing factor quantity demand equations can then be obtained by invoking Shephard's Lemma, differentiating (16) with respect to $p_1, p_2, \ldots, p_{n-1}, p_n$. Note that these factor quantity demand equations will have as a right-hand variable the quality-adjusted price p_n^*, which by (20) is in turn a function of engineering characteristics and the price of energy. Hence cost-minimizing factor quantity demand equations are a function of both input prices and input quality.

III. TOWARDS AN EMPIRICAL IMPLEMENTATION

In the previous section we have presented a general analytical framework for incorporating quality aspects into the theory of cost and production, and occasionally have commented on how this synthesis could be useful for understanding the effects of energy price changes on the quality of capital. In this section we consider issues of empirical implementation in further detail.

Assume that in the short run the firm's optimization behavior involves minimizing costs of variable inputs L (labor), E (energy) and non-energy intermediate materials (M). Given output level Y, these mimimum variable costs, the stock of quality-adjusted capital K*, and the state of technology (t) can be represented by the variable cost function $VC = g(P_L, P_E, P_M, K^*, Y, t)$ which we specify to be of the translog form:[7]

$$
\begin{aligned}
(21) \qquad \ln CV = {} & \alpha_o + \alpha_Y \ln Y + \sum_i a_i \ln P_i + \beta_K \ln K^* + \alpha_t t + \frac{1}{2} \alpha_{tt} t^2 + \frac{1}{2} \gamma_{YY} (\ln Y)^2 \\
& + \frac{1}{2} \sum_i \sum_j \gamma_{ij} \ln P_i \ln P_j + \frac{1}{2} \delta_{KK} (\ln K^*)^2 + \sum_i \rho_{Yi} \ln Y \ln P_i \\
& + \beta_{YK} \ln Y \ln K^* + \sum_i \rho_{Ki} \ln K^* P_i + \rho_{TY} \cdot t \cdot \ln Y + \rho_{TK} \cdot t \cdot \ln K^* \\
& + \sum_i \rho_{Ti} \ln P_i \,, \qquad\qquad i = L, E, M
\end{aligned}
$$

where $\gamma_{ij} = \gamma_{ji}$. Constant returns to scale on the dual production function $Y = f(K^*, L, E, M)$ imposes the following restrictions on (21):

$$(22)\qquad \alpha_Y + \beta_K = 1 \qquad \rho_{Yi} + \rho_{Ki} = 0, \qquad i = L, E, M$$

$$\gamma_{YY} + \rho_{YK} = 0 \qquad \rho_{YK} + \delta_{KK} = 0, \qquad \rho_{TY} + \rho_{TK} = 0$$

We now specify the form of the hedonic capital quality-adjustment as multiplicative factor augmenting,

$$(23)\qquad K_t^* = K_t h(P_{Et}, P_{E,t-\tau})^{b_{KE}}$$

$$= K_t \mathrm{EEIR}_t^{b_{KE}}$$

where the variable EEIR_t--to be discussed in further detail in the next section--measures the energy inefficiency of the existing capital stock and thus is a function of current energy prices relative to energy prices existing when vintages of capital surviving to time t were originally acquired, and b_{KE} is a parameter to be estimated. Taking logarithms of (23) yields

$$(24)\qquad \ln K_t^* = \ln K_t + b_{KE} \ln \mathrm{EEIR}_t \quad .$$

A priori, we expect that as the embodied energy inefficiency of the capital stock increases, the quality-adjusted measure of capital declines, i.e., we expect $b_{KE} < 0$. Note that if $b_{KE} = 0$, traditional and quality-adjusted measures of capital coincide.

We now substitute (24) into (21), and then impose the condition that variable costs are homogeneous of degree one in prices given output and capital quality. This implies the restrictions

$$(25)\qquad \begin{aligned} &\sum_i \rho_{Ti} + b_{KE}\rho_{TK} = 0, \\ &\sum_i \rho_{Ki} + b_{KE}\gamma_{YY} = 0, \\ &\sum_i \gamma_{ij} + b_{KE}\rho_{Ki} = 0, \\ &\sum_i \alpha_i + b_{KE}\beta_K = 1, \qquad\qquad i, j = L, E, M. \end{aligned}$$

The shadow value of capital relationship (the reduction in variable costs realized by increasing the quantity of capital K, holding output quantity and input prices fixed) is obtained by logarithmically differentiating (21) with respect to K, and is denoted as SH_K. When the restrictions (22), (24) and (25) are imposed, SH_K turns out to be

$$(26)\qquad SH_K = \frac{\partial \ln CV}{\partial \ln K} = \frac{\partial CV}{\partial K} \cdot \frac{K}{CV} = \frac{-P_K \cdot K}{CV}$$

$$= \beta_K + \rho_{KL}\ln(\frac{P_L}{P_M}) + \rho_{KE}\ln(\frac{P_E}{P_M}) + \gamma_{YY}b_{KE}\ln(\frac{EEIR}{P_M}) + \gamma_{YY}\ln(\frac{K}{Y}) + \rho_{TK} \cdot t$$

where P_K is the quality-unadjusted shadow value of capital. The cost-minimizing share equations for the variable inputs L, M and E are obtained by logarithmically differentiating the variable cost function (21) (with restrictions (22), (24) and (25) imposed) with respect to the prices of the variable inputs, using Lau's [1978] variant of Shephard's Lemma for the restricted cost function:

$$(27) \qquad S_L = \frac{\partial \ln CV}{\partial \ln P_L} = \frac{P_L L}{CV} = \alpha_L + \gamma_{LL}\ln(\frac{P_L}{P_M}) + \gamma_{LE}\ln(\frac{P_E}{P_M}) + \rho_{KL}b_{KE}\ln(\frac{EEIR}{P_M})$$

$$+ \rho_{KL}\ln(\frac{K}{Y}) + \rho_{LT} \cdot t$$

$$S_M = \frac{\partial \ln CV}{\partial \ln P_M} = \frac{P_M M}{CV} = \alpha_M + \gamma_{LM}\ln(\frac{P_L}{P_M}) + \gamma_{EM}\ln(\frac{P_E}{P}) + \rho_{KM}b_{KE}\ln(\frac{EEIR}{P})$$

$$+ \rho_{KM}\ln(\frac{K}{Y}) + \rho_{MT} \cdot t$$

$$S_E = \frac{\partial \ln CV}{\partial \ln P_E} = \frac{P_E E}{CV} = \alpha_E + \gamma_{LE}\ln(\frac{P_L}{P_M}) + \gamma_{EE}\ln(\frac{P_E}{P_M}) + \rho_{KE}b_{KE}\ln(\frac{EEIR}{P_M})$$

$$+ \rho_{KE}\ln(\frac{K}{Y}) + \rho_{ET} \cdot t + b_{KE}SH_K$$

A number of issues merit discussion concerning the share equation system (26) and (27). First, when the restrictions in (25) are imposed, the variable input shares S_L, S_E, and S_M in (27) sum to unity; this implies that only two of the three shares are linearly independent. Second, these variable input share equations depend not only on prices of variable inputs and the quantity of capital, but also on the quality of capital. To see this, substitute back from (27) to (24), for example, and obtain for the labor share equation in (27),

$$S_L = \alpha_L + \gamma_{LL}\ln(\frac{P_L}{P_M}) + \gamma_{LE}\ln(\frac{P_E}{P_M}) + \rho_{KL}\ln(\frac{K^*}{Y}) + \rho_{LT} \cdot t$$

which makes more clear the quantity-quality interaction in this factor demand model. This implies that capital quality can be inferred indirectly using (24) and the parameter estimate of b_{KE}.

Third, the capital quality parameter b_{KE} from (24) appears in each of the variable input cost share equations in (27) as well as in the SH_K shadow cost share equation (26); this implies testable cross-equation restrictions. Fourth, energy price increases have direct and indirect effects on the variable input share equations; the direct effect is the traditional short-run substitution effect induced by energy price changes, while the indirect effect is via the induced reduction in capital quality generated by the energy price increases. Further, if $b_{KE} = 0$, the indirect effect drops out of (27), and the specification thus reverts to traditional translog demand system forms. Fifth and finally, if one estimated the shadow share (26) and two of the three linearly independent variable cost share equations in (27), implicitly one would be assuming that input prices for L, E, and M, the quantity of output, and the quantity and quality of capital are exogenous in the short-run, while the input quantities of L, E, and M are endogenous, along with the shadow value of capital. Hence a particularly attractive feature of this model is that the shadow value of capital depends on the energy price-dependent quality of capital.

Having outlined our empirically implementable capital quality-quantity model, we now turn to a consideration of the measurement of the important EEIR variable--the embodied energy inefficiency ratio of the capital stock.

IV. CONSTRUCTION OF THE EEIR INDEX

The relationship between energy and capital is a special one. *Ex ante*, there are substantial possibilities for capital-energy substitution. Typically the more energy-efficient equipment types entail a larger initial acquisition cost, *ceteris paribus*. Once capital equipment is installed, however, the amount of energy consumed per unit of work output is largely "tied" to the engineering design and performance characteristics embodied in the installed equipment. While possible, retrofitting of existing equipment is increasingly costly at the margin, and is therefore limited. Hence, *ex post*, capital-energy relations are largely fixed. In this section we develop procedures that attempt to measure the energy efficiency embodied in the *ex post* aggregate capital stock. While our approach is outlined here, further details are available in Appendix B to this paper.

Assume that at time $t-\tau$, based on such considerations such as expected output demand and labor costs, firms decide on the amount and durability of the investment they will undertake, and then choose the optimal energy efficiency of the new equipment or structures investment. Let there be nonzero energy-capital substitutability *ex ante*, but once the vintage $t-\tau$ investment is put in place, the energy per unit of capital work ratio is fixed for each vintage until it is scrapped. Assume also that the optimal energy efficiency choice depends on the price of energy relative to the asset price of the new investment equipment on structures, and denote this relative energy price as

$$p_{E,t-\tau} = \frac{P_{E,t-\tau}}{P_{\text{Equip} \quad \text{or Struc}}} \, .$$

With myopic relative energy price expectations, the optimal energy per unit of capital ratio at time $t-\tau$ is a decreasing function of $p_{E,t-\tau}$. Given these assumptions, once the investment is made at time $t - \tau$, this energy efficiency becomes embodied in the installed capital stock surviving into future time periods.

Let δ be the constant annual rate of physical geometric deterioration for fixed capital. Assume that scrappage occurs once 95 percent of the asset has physically deteriorated, and denote the resulting physical lifetime in years as T. The survival rate of capital of age τ is denoted as s_τ, i.e.

$$(28) \qquad s_\tau = (1 + \delta)^{-\tau},$$

and the amount of vintage $t - \tau$ investment surviving to time t, $K_{t,t-\tau}$, is therefore

$$(29) \qquad K_{t,t-\tau} = s_\tau I_{t-\tau}$$

where $I_{t-\tau}$ is real investment at time $t - \tau$.

The traditional capital accounting procedures assume that up to a factor of proportionality (the survival rates), the various vintages of capital are perfectly substitutable and therefore summable, i.e., aggregate capital K_t is simply the sum over surviving vintages,

$$(30) \qquad K_t = \sum_{\tau=0}^{T} K_{t,t-\tau} .$$

As pointed out in Berndt [1983b, Section III], this traditional procedure assumes that conversion ratios between two vintages of capital depend only on their age differences and δ, and thus are independent of energy prices.

Recalling our earlier discussion on relative energy-capital prices of various vintages embodied in the aggregate capital stock, let us denote the weighted average of vintage-specific relative energy prices embodied in the capital stock surviving to time t as

$$(31) \quad \hat{K}_t = \sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau} .$$

Note that $\hat{K}_t$ obviously reflects the history of energy prices relative to new capital goods prices, and thus is inversely related to the energy efficiency embodied in the aggregate vintage-weighted capital stock.

Now suppose that instead of changing over time, the relative price of energy at time t - τ had been constant at its level at time t, i.e., $p_{E,t-\tau} = p_{E,t}$, $\tau = 1,\ldots,T$. Obviously, had this occurred, the firm choosing the optimal energy efficiency for its plant and equipment would have chosen a different energy efficiency than was done historically when $p_{E,t-\tau} \neq p_{E,t}$. Had the relative energy price remained constant, however, the weighted average of vintage-specific relative energy prices embodied in the aggregate capital stock surviving to time t would have been

$$(32) \quad K'_t = \sum_{\tau=0}^{T} p_{E,t} K_{t,t-t} = p_{E,t} \sum_{\tau=0}^{T} K_{t,t-\tau} = p_{E,t} K_t .$$

Since optimal energy efficiency at time t-τ is a decreasing function of $p_{E,t-\tau}$, it follows that the ratio of the energy-efficiency embodied in the aggregate surviving capital stock under constant (time t) relative energy prices (K'_t) to the energy efficiency embodied in the aggregate surviving capital stock given actual historical relative energy prices ($\hat{K}_t$) yields an index of the energy inefficiency of the current aggregate stock. We therefore define the embodied energy inefficiency ratio EEIR as

$$(33) \qquad EEIR_t = \frac{K'_t}{\hat{K}_t} = \frac{\sum_{t=0}^{T} p_{E,t} K_{t,t-\tau}}{\sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau}} = \frac{p_{E,t} K_t}{\sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau}} \quad .$$

In interpreting (33), note that if relative energy prices had been constant for a long time and then suddenly increased at time t, i.e., if $p_{E,t} > p_{E,t-\tau}, \tau = 1,\ldots,T$, then $EEIR_t > 1$--by current p_{Et} standards, the capital stock would be energy-inefficient. Conversely if after a period of constant relative energy prices p_E suddenly fell, i.e., if $p_{E,t} < p_{E,t-\tau}$, then by current p_{Et} standards the capital stock would be too energy-efficient, i.e., $EEIR_t < 1$. It follows that if relative energy prices remained constant over at least T time periods, then the surviving capital stock at time t would have an $EEIR_t = 1$. Finally, note that if energy efficiency improvements occurred over time in an autonomous manner of the, say, Hicks-neutral technical progress form, then this effect of technical progress would appear both in (31) and in (32), and thus would cancel out in the EEIR ratio form (33).

Before presenting data details on the construction of the EEIR ratio, it is useful briefly to relate EEIR to the classic issues of capital aggregation over vintages. Recall from (24) that the capital quality adjustment relationship used here is of the form

$$(24) \quad \ln K_t^* = \ln K_t + b_{KE} \ln EEIR_t \ ,$$

where EEIR is defined in (33). Define a more general vintage quality-weighted capital stock surviving to time t as $\tilde{K}_t$,

$$(34) \quad \tilde{K}_t = \sum_{\tau=0}^{T} e_{t,t-\tau} K_{t,t-\tau}$$

where the $e_{t,t-\tau}$ are vintage and time-specific quality weights. As is shown in Appendix B, one can attempt to relate these $e_{t,t-\tau}$ weights to the relative energy price weights of the EEIR index (33) and the relationship (24). This yields

$$(35) \quad \sum_{\tau=0}^{T} e_{t,t-\tau}\left(\frac{K_{t,t-\tau}}{K_t}\right) = \left[\sum_{\tau=0}^{T}\left(\frac{p_{E,t-\tau}}{p_{E,t}}\right)\left(\frac{K_{t,t-\tau}}{K_t}\right)\right]^{-b_{KE}}$$

which suggests that in general one cannot solve analytically for the $e_{t,t-\tau}$ weights as a function of b_{KE} and relative energy prices.

Two special cases of (35) are, however, of particular interest. First, if $b_{KE} = 0$, then $e_{t,t-\tau} = 1$ for all t,τ. In this case, if relative energy prices do not affect capital quality--see (24)--the time and vintage-specific weights all equal unity, and K^*_t and K_t coincide. This case is that assumed by traditional capital measurement procedures.

Second, if however $b_{KE} = -1$, then it turns out that the time and vintage-specific capital quality weights are precisely inversely proportional to the relative energy prices, i.e., in this case

$$(36) \qquad e_{t,t-\tau} = \frac{p_{E,t-\tau}}{p_{E,t}} , \qquad\qquad \tau = 0,\ldots, T.$$

This intuitively appealing situation is an example of what Berndt [1983b] calls <u>price-dependent quality adjustment</u>. Further discussion of these issues is found in Berndt and in Appendix B of this paper.

Regarding data sources, as discussed in Appendix B, measures of geometric physical deterioration based on the Winfrey mortality distribution and OBE net capital stock estimates are .135 for producers' durable equipment (EQ) and .071 for nonresidential structures (ST), which implies that physical scrappage (when 95 percent of the asset is physically deteriorated) occurs after 21 years for EQ and 41 years for ST.

Investment data in current and constant dollars for EQ and ST in U.S. manufacturing since the late 1800's to 1979 were kindly provided us by Mr. J. Silverstein of the BEA at the U.S. Department of Commerce. This investment series was used to compute the implicit deflators (normalized to unity in 1972) for equipment and structures.

The necessary energy price data for U.S. manufacturing was required back to 1906, since the physical lifetimes of ST are 41 years and our principal data sample begins in 1947. While details are provided in Appendix A, here we briefly note that these series were constructed using data from various Census of Manufactures back to 1909, the Edison Electric Institute, and data presented in the historical study by Schurr-Netschert

[1960]. The aggregate energy price P_E is calculated as a Divisia index of bituminous coal, anthracite coal, crude oil and oil products, natural gas, and purchased plus non-thermally self-generated electricity, and is normalized to unity in 1972. Energy data for 1947-71 are taken from Berndt-Wood [1975], and then are spliced with the Norsworthy-Harper [1981] data to 1977.[8]

Because the P_E, P_{EQUIP}, and P_{STRUC} data series are of particular interest in this study, we reproduce here from Appendix A Table 1 (1906-47) and Table 2 (1947-77). A number of observations are worthy of note. With some slight aberrations, since the early 1920's and until 1970 the ratio P_E/P_{EQUIP} fell; by 1977, however, it approximately doubled its 1970 value. For P_E/P_{STRUC} the story is somewhat similar, again generally falling from the early 1920's to a minimum value in 1970, and then not quite doubling by 1977. The year 1970 is therefore a significant turning point. Note also that while the time trend for P_E relative to P_{EQUIP} and P_{STRUC} is similar, from 1906 to 1947 and especially from 1922 to 1947, the price of new equipment fell relative to the price of new structures. Finally, note that in the 1917-20 time period, there occurred a very sharp increase in energy prices, due in part to wartime shortages and a coal strike. Hence the 1973-74 energy price shock had a slightly weaker precedent in the U.S. about 55 years earlier.

TABLE 1

PRICE INDEXES FOR ENERGY, NEW EQUIPMENT, AND NEW STRUCTURES IN U.S. MANUFACTURING, 1906-1947

YEAR	PE	PEQUIP	PSTRUC	PE/PEQUIP	PE/PSTRUC
1906	.3539	.1285	.1170	2.754	3.024
1907	.3646	.1390	.1170	2.624	3.115
1908	.3587	.1299	.1135	2.761	3.161
1909	.3446	.1464	.1142	2.354	3.017
1910	.3552	.1470	.1170	2.416	3.036
1911	.3544	.1632	.1170	2.172	3.028
1912	.3702	.1561	.1220	2.372	3.034
1913	.3814	.1532	.1348	2.498	2.831
1914	.3754	.1633	.1199	2.298	3.131
1915	.3519	.1803	.1220	1.952	2.884
1916	.3902	.1968	.1461	1.983	2.671
1917	.5533	.2444	.1752	2.264	3.159
1918	.6231	.3163	.2000	1.970	3.116
1919	.6202	.3257	.2340	1.904	2.650
1920	.8394	.3356	.3022	2.501	2.778
1921	.6705	.3118	.2192	2.150	3.059
1922	.6926	.2719	.2105	2.547	3.290
1923	.6175	.2856	.2384	2.162	2.590
1924	.5589	.2887	.2340	1.936	2.389
1925	.5511	.2904	.2340	1.898	2.355
1926	.5676	.2891	.2341	1.963	2.425
1927	.5218	.2892	.2290	1.804	2.278
1928	.4975	.2911	.2291	1.709	2.171
1929	.4893	.3082	.2241	1.588	2.183
1930	.4808	.2916	.2107	1.649	2.282
1931	.4449	.2673	.1830	1.664	2.431
1932	.4471	.2429	.1546	1.841	2.892
1933	.4103	.2314	.1489	1.773	2.755
1934	.4514	.2728	.1703	1.654	2.651
1935	.4410	.2762	.1703	1.597	2.589
1936	.4296	.2763	.1816	1.555	2.365
1937	.4358	.2969	.2071	1.468	2.105
1938	.4419	.3095	.2037	1.428	2.169
1939	.4147	.3091	.2014	1.341	2.059
1940	.4078	.3259	.2099	1.251	1.942
1941	.4210	.3498	.2319	1.204	1.816
1942	.4214	.3599	.2638	1.171	1.597
1943	.4335	.3589	.2966	1.208	1.461
1944	.4452	.3592	.2840	1.239	1.568
1945	.4579	.3572	.2863	1.282	1.600
1946	.4983	.3886	.3107	1.282	1.603
1947	.5589	.4071	.3803	1.373	1.470

TABLE 2

PRICE INDEXES FOR ENERGY, NEW EQUIPMENT, AND NEW STRUCTURES IN U.S. MANUFACTURING, 1947-1977

YEAR	PE	PEQUIP	PSTRUC	PE/PEQUIP	PE/PESTRUC
1947	.5589	.4071	.3803	1.373	1.470
1948	.7280	.4591	.4261	1.586	1.709
1949	.6688	.4921	.4265	1.359	1.568
1950	.6788	.5070	.4298	1.339	1.579
1951	.6996	.5511	.5271	1.269	1.327
1952	.7150	.5586	.5473	1.280	1.306
1953	.7126	.5708	.5493	1.249	1.297
1954	.7286	.5783	.5329	1.260	1.367
1955	.7505	.6103	.5455	1.230	1.376
1956	.7666	.6576	.5860	1.166	1.308
1957	.7714	.7024	.6116	1.098	1.261
1958	.7788	.7216	.5959	1.079	1.307
1959	.7643	.7436	.5772	1.028	1.324
1960	.7714	.7561	.5680	1.020	1.358
1961	.7692	.7599	.5591	1.012	1.376
1962	.7696	.7695	.5603	1.000	1.373
1963	.7531	.7712	.5847	.976	1.288
1964	.7767	.7807	.6115	.995	1.270
1965	.7748	.7951	.6300	.975	1.230
1966	.7830	.8204	.6609	.954	1.185
1967	.7780	.8505	.6941	.915	1.121
1968	.8014	.8727	.7167	.918	1.118
1969	.8187	.9025	.8016	.907	1.021
1970	.8155	.9442	.8783	.864	.928
1971	.9205	.9812	.9534	.938	1.065
1972	1.0000	1.0000	1.0000	1.000	1.000
1973	1.1254	1.0272	1.0973	1.096	1.026
1974	1.5484	1.1235	1.1938	1.378	1.297
1975	1.9586	1.3102	1.4080	1.495	1.391
1976	2.1627	1.4017	1.3860	1.543	1.560
1977	2.5171	1.4801	1.4664	1.701	1.717

Based on these relative energy price series and the corresponding investment data, separate EEIR indexes for equipment and structures covering the 1947-77 time period were constructed using (33). Since the largest amount of energy use is associated with equipment rather than structures, an aggregate EEIR index was constructed weighting that for equipment by 0.85 and that for structures 0.15. As is discussed in Appendix B, however, the aggregate EEIR data series do not appear to be very sensitive to a variety of alternative plausible weighting schemes. The resulting EEIR data series is reproduced from Appendix B and presented in Table 3 below. Note that the EEIR ratio falls from about 1.07 in 1948 to .868 in 1959, rises to .929 in 1964, gradually falls to .889 in 1970, and then rises sharply from 1.097 in 1973 to 1.298 in 1974 and 1.338 in 1977.

Table 3

Embodied Energy Inefficiency Ratio of the
Fixed Capital Stock in U.S. Manufacturing, 1947-77

Year	EEIR	Year	EEIR	Year	EEIR
1947	0.956	1958	0.885	1969	0.916
1948	1.070	1959	0.868	1970	0.889
1949	0.941	1960	0.882	1971	0.968
1950	0.941	1961	0.895	1972	1.024
1951	0.889	1962	0.903	1973	1.097
1952	0.910	1963	0.896	1974	1.298
1953	0.908	1964	0.929	1975	1.311
1954	0.935	1965	0.919	1976	1.300
1955	0.927	1966	0.913	1977	1.338
1956	0.896	1967	0.896		
1957	0.871	1968	0.920		

V. ECONOMETRIC IMPLEMENTATION AND RESULTS

In the previous section we elaborated on the construction of the EEIR index, along with other related data. In this section we first discuss two alternative measures of the shadow cost of capital—one based on Christensen-Jorgenson's procedures using ex post internal rate of return data from the National Income and Product Accounts, and the other based on ex post stock market data as collected by Holland-Myers [1979, 1980]. Next we review some econometric issues, and present alternative estimates of parameters--especially b_{KE}--given the two alternative shadow cost of capital data series. Finally, we present implied estimates of the energy price quality-adjusted and traditional capital stock measures.

Earlier we noted that the shadow value or shadow cost of quality-unadjusted capital was endogenous in our model, and that in particular it depended on K_t, P_{Et} (therefore K^*_t), P_{Lt}, P_{Mt}, Y_t, and t. Empirically, two alternative measures of the shadow cost of capital--hereafter, P_K--are available to us.

The first measure is the one-period ex post rental price of capital computed using the Christensen-Jorgenson [1969] formulae, historical National Income and Product Account (hereafter, NIPA) data, including in particular the ex post before-tax nominal rate of return on the beginning-of-year capital stock, and effective tax rates. These formulae, rate of return and tax data were used by us in our earlier studies (see, for example, Berndt-Wood [1975, 1979]), but it is important to emphasize here that in this study the ex post internal rate of return nature of the data is particularly attractive in that it captures the endogeneity of P_K as a function of the right-hand variables in (26). Updated series to 1977 on these rate of return and tax data have kindly been provided us by Dale W. Jorgenson and Barbara Fraumeni, and we have used them to construct one-period (rental) prices for equipment and structures, and then used a Divisia price aggregation procedure to form the aggregate capital shadow price. Hereafter we denote this capital expenditure series as $P_K K$(NIPA).

The second measure of the shadow cost of capital is based on the securities' market data for manufacturing collected and presented by Holland-Myers [1979, 1980], with updates kindly provided us by the authors. Holland-Myers estimate the values of debt and equity capital for U.S. manufacturing firms, 1947-76, as well as the implied <u>ex post</u> average rates of return earned by investors in these markets. These securities' market valuations of capital are divided by the estimated replacement value of capital to obtain a measure of Tobin's q.[9] Since our capital stock data refer only to equipment and structures, we use the Holland-Myer estimate of Tobin's q for U.S. manufacturing to obtain the implied market value of only the equipment and structures portion of the manufacturing capital stocks. This procedure assumes implicitly that the Tobin's q values are equal across different assets (equipment, structures, land, inventories, etc.) in the manufacturing sector. The resulting securities' market valuation of the numerator of the shadow cost share--see (26)—is denoted $P_K K$ (MARVAL). Note that this shadow value estimate incorporates not only current profitability, but also the expected profitability in the future.

We now turn to a brief discussion of econometric issues. We estimate parameters in the shadow cost share equation (26) and two of the three (specifically, S_L and S_E) variable input cost share equations in (27). First, identification of parameters--especially b_{KE}--is not possible if only the variable input cost share equations S_L and S_E are estimated. Second, partly because of the direct plus indirect effects of energy price changes on factor demands, the S_E equation in (27) has as a regressor the capital shadow share SH_K. Hence, it would appear that we are subject to a simultaneous equations system estimation problem. If, however, an additive disturbance term is added to the SH_K, S_L and S_E equations in (26) and (27), and if in addition the resulting disturbance vector is assumed to be independently and identically multivariate normally distributed with mean vector zero and constant nonsingular covariance matrix, the Jacobian matrix in the implied log-likelihood function turns out to be triangular, implying that estimation by the iterated "seemingly unrelated" Zellner estimation method is numerically equivalent to estimation by full-information maximum likelihood. Intuitively, this triangularity occurs because the equation system in (26) - (27) is structurally recursive; while S_E depends on SH_K, SH_K is not a function of S_L or S_E.

We have estimated the SH_K, S_L, and S_E equation system in (26) - (27) by the method of maximum likelihood, using annual U.S. manufacturing data, 1947-77. Initial runs suggested the possibility of multiple local optima, primarily due to the nonlinear relationship in b_{KE}.[10] As a precaution, therefore, we estimated the equation system over a grid of b_{KE} values--from $b_{KE} = 0.25$ to $b_{KE} = -1.25$--in steps of 0.05. This provided us with an indication of where the "global" sample log-likelihood was most likely to occur. Using those "global" values of b_{KE} as starting values, we then converged easily to a local--hopefully, global--sample log-likelihood maximum. Parameter estimates using the NIPA and MARVAL capital shadow cost estimates are presented in Table 4.

As is seen in the second column of Table 4, the two alternative estimates of b_{KE} are each negative and statistically significantly different from zero.[11] Based on the ex post internal rate of return on the beginning of year capital stock and data from the National Income and Product Accounts

Table 4

Maximum Likelihood Estimated Parameters of Short-Run Cost Function Model NIPA and MARVAL Estimates of Shadow Cost Share U.S. Manufacturing, 1947-77

(Asymptotic t-statistics in parentheses)

Parameter	NIPA Estimate	MARVAL Estimate	Parameter	NIPA Estimate	MARVAL Estimate
β_K	-.1095	.2595	ρ_{TM}	.0038	.0033
	(2.06)	(4.82)		(5.44)	(4.53)
α_L	.4594	.3562	b_{KE}	-.3005	-.8500
	(10.68)	(9.98)		(12.74)	(61.59)
α_E	.0537	.3019	γ_{YY}	-.0188	.1143
	(2.69)	(6.27)		(0.98)	(5.49)
α_M	.1535	-.2875	γ_{LL}	.2249	.1860
	(2.94)	(7.32)		(8.00)	(6.78)
ρ_{KL}	.0172	-.0127	γ_{LE}	-.0198	-.0270
	(1.30)	(1.35)		(2.59)	(2.86)
ρ_{KE}	.0143	.1119	γ_{LM}	-.1999	-.1698
	(2.00)	(6.47)		(6.26)	(5.45)
ρ_{KM}	-.0372	-.0021	γ_{EE}	.0454	.1398
	(2.60)	(0.20)		(12.11)	(9.53)
ρ_{TK}	-.0006	-.0026	γ_{EM}	-.0212	-.0176
	(1.79)	(5.57)		(2.16)	(1.56)
ρ_{TL}	-.0044	-.0034	γ_{MM}	.2100	.1856
	(7.21)	(5.47)		(5.49)	(4.94)
ρ_{TE}	.0004	-.0019	ln L	374.377	357.022
	(2.05)	(4.87)			

(NIPA), the maximum likelihood estimate of b_{KE} is -.30, while using the *ex post* rate of return on financial investments in the U.S. manufacturing securities and market value data (MARVAL), the estimate of b_{KE} jumps considerably to -.85. These two numbers each appear to be statistically significant, but their absolute values differ somewhat; their difference could reflect the effects of nonstatic expectations in the securities' markets.[12]

Given these two alternative estiates of b_{KE}, we next use equation (24) to calculate quality-adjusted measures of capital, and then compare these to traditional quality-unadjusted measures. Results are presented in Table 5.

The entries in Table 5 are most interesting and provocative. Traditionally measured, the net capital stock grew 146 percent from 1947-70, and an additional 14.4 percent from 1970 to 1977; the corresponding average annual growth rates are 4.0 percent (1947-70) and 1.9 percent (1970-77). If one quality-adjusts the capital for its embodied energy inefficiency, however, over the 1947-70 growth rates are increased only slightly—4.1 percent (NIPA) and 4.3 percent (MARVAL). This increase occurs because the quality of capital was augmented during the 1947-70 time period due to reductions in current relative energy prices.

More dramatic changes appear, however, once one examines the post-1970 data. In contrast to the traditional capital stock accounting procedure which indicates a 1.9 percent average annual growth rate 1970-77, the quality-adjusted average annual growth rates in capital are only 0.2 percent (NIPA) and -3.0 percent (MARVAL). Hence, with the NIPA-based estimate of b_{KE} the implied quality-adjusted capital stock remains essentially stagnant over the 1970-77 time period, the MARVAL-based estimate capital stock declines 24 percent from 1970 to 1977, while the traditionally measured capital stock grows 14 percent. Note also that as a percentage of

Table 5

Traditional and Quality-Adjusted Measures of the Fixed Capital Stock Based on NIPA and MARVAL-based Estimates of b_{KE} U.S. Manufacturing, 1947-77

	K Traditional	K*-NIPA Quality-Adjusted	K*-MARVAL Quality-Adjusted
1947	21.86	22.16	22.73
1948	25.59	25.07	24.15
1949	27.83	28.34	29.29
1950	28.57	29.10	30.09
1951	29.14	30.19	32.21
1952	30.55	31.43	33.10
1953	31.74	32.68	34.47
1954	32.80	33.47	34.74
1955	33.83	34.61	36.07
1956	34.70	35.87	38.10
1957	36.40	37.94	40.92
1958	37.93	39.36	42.10
1959	38.08	39.74	42.96
1960	37.97	39.43	42.25
1961	38.31	39.61	42.10
1962	38.50	39.70	41.98
1963	38.92	40.23	42.73
1964	39.62	40.51	42.17
1965	40.92	41.97	43.97
1966	43.29	44.49	46.78
1967	46.56	48.12	51.10
1968	49.57	50.83	53.22
1969	51.68	53.07	55.71
1970	53.77	55.71	59.43
1971	55.10	55.64	56.65
1972	55.49	55.09	54.38
1973	56.17	54.63	51.92
1974	57.93	53.58	46.44
1975	59.79	55.12	47.50
1976	60.04	55.49	48.04
1977	61.51	56.36	48.03

the 1977 quality-unadjusted capital stock, the NIPA and MARVAL-based estimates are 8.4 and 21.9 percent less, respectively. This implies that somewhere between 8 and 22 percent of the traditionally measured capital stock was "blown-up" by OPEC-induced and other energy price increases since 1970.

We conclude, therefore, that capital stock measures since 1970 in U.S. manufacturing differ substantially depending on whether and how one adjusts for the decline in quality of the surviving vintages of capital stock, most of which were acquired when relative energy prices were much lower than after 1970.

VI. IMPLICATIONS FOR PRODUCTIVITY MEASUREMENT

Multifactor productivity growth ($\dot{A}/A$) is typically calculated as growth in aggregate output ($\dot{Y}/Y$) minus growth in aggregate input ($\dot{X}/X$), where $\dot{X}/X$ is a Divisia share-weighted growth of the individual inputs.[13] In the context of our K, L, E, M model, therefore, multifactor productivity is computed as:

$$(37) \qquad \frac{\dot{A}}{A} = \frac{\dot{Y}}{Y} - \frac{\dot{X}}{X} = \frac{\dot{Y}}{Y} - \overline{S}_K \frac{\dot{K}}{K} - \overline{S}_L \frac{\dot{L}}{L} - \overline{S}_E \frac{\dot{E}}{E} - \overline{S}_M \frac{\dot{M}}{M}$$

where $\overline{S}_i$, i = K, L, E, M are the arithmetic means of input cost shares in periods t and t - 1. Note that if the rate of growth of $\dot{K}/K$ differs from that of $\dot{K}^*/K^*$ (quality-adjusted capital), then traditional multifactor productivity measures may yield results different from those that account for capital quality change.

Specifically, denote quality-adjusted multifactor productivity as $\dot{A}^*/A^*$, and define it as in (37) except replace $\dot{K}/K$ with $\dot{K}^*/K^*$; note that $\overline{S}_K$ is unaffected by this, since price times quantity is invariant to quality measurement. By (24), it follows that

$$(38) \qquad \ln\left(\frac{K_t^*}{K_{t-1}^*}\right) - \ln\left(\frac{K_t}{K_{t-1}}\right) = \bar{S}_{K,t}\, b_{KE} \ln\left(\frac{EEIR_t}{EEIR_{t-1}}\right) ,$$

which implies that

$$(39) \qquad \frac{\dot{A}}{A} - \frac{\dot{A}^*}{A^*} = S_{K,t}\, b_{KE} \left(\frac{\dot{EEIR}}{EEIR}\right).$$

To interpret (39), note that when the embodied energy inefficiency increases due to, say, an energy price increase, ($\dot{EEIR}/EEIR > 0$), the growth of quality-adjusted capital falls (since $b_{KE} < 0$), which implies that growth in quality-adjusted aggregate input falls, and that quality-adjusted multifactor productivity (growth in aggregate output minus growth in quality-adjusted aggregate input) increases, i.e., in this case $\dot{A}/\dot{A} - \dot{A}^*/\dot{A}^* < 0$, quality-adjusted multifactor productivity growth is underestimated because of energy price changes.

That energy price changes may have changed the capital stock quality is not an original hypothesis,[14] but to date hardly any empirical analysis has been devoted to it. Hence it is of interest to examine whether and how much, especially since 1973, multifactor productivity growth has been underestimated.

Evidence on this issue is presented in Table 6. The top panel of this table presents levels of multifactor productivity (normalized to unity in 1972) using traditional procedures (column 1), quality-adjusted NIPA capital data (column 2), and quality-adjusted MARVAL capital (column 3). These entries can be used to compute average annual growth rates (AAGR) over various time intervals. In the bottom panel of Table 2 we present such calculations for a number of subperiods, which we now discuss.

Comparison across columns in the bottom panel of Table 6 indicates that over the 1948-56, 1956-67 and 1967-70 time periods, there is very little difference amongst the three alternative multifactor productivity growth measures; all show growth of around 1.0 percent per year 1948-56, 0.8 percent per year 1956-67, and 0.6 percent per year 1967-70. Beginning in 1970, however (when the energy relative price measures hit their 1906-77 historical minimum), considerable dispersion emerges. The traditional $\dot{A}/A$ measure indicates an AAGR of -0.20 percent 1970-73, while $\dot{A}^*/A^*$ (NIPA) is less negative at -0.13 percent, and $\dot{A}^*/A^*$ (MARVAL) is positive at 0.07 percent; for all three measures, the 1970-73 values represent a sharp drop from the 1967-70 time interval. Of particular interest, however, is the significant difference amongst productivity measures over the post-OPEC 1973-77 time span. Here traditional $\dot{A}/A$ is 0.10 percent, $\dot{A}^*/A^*$ (NIPA) is considerably larger at 0.27 percent, and $\dot{A}^*/A^*$ (MARVAL) is more than five times larger than the traditional measure at 0.51 percent per year. Note that under the $\dot{A}^*/A^*$ (MARVAL) measure, multifactor productivity growth 1973-77 at 0.51 percent per annum is almost the same as growth in the 1967-70 time span at 0.56 percent per year. Hence, with the MARVAL quality-adjusted capital data the multifactor productivity slowdown mystery since 1967 is confined only to the brief 1970-73 interval.

We conclude, therefore, that while there appears to have been a gradual slowdown in multifactor productivity growth since 1948, the alleged post-1973 slowdown may be viewed in no small part as a measurement problem in failing to take account of the reduction in the growth of quality-adjusted capital induced by energy price increases that began as

Table 6

Traditional and Quality-Adjusted Measures of Multifactor Productivity U.S. Manufacturing, 1948-77

	A Traditional	A*-NIPA Quality-Adjusted	A*-MARVAL Quality-Adjusted
1948	.840	.840	.839
1949	.837	.839	.843
1950	.852	.852	.851
1951	.869	.869	.868
1952	.885	.884	.881
1953	.889	.888	.886
1954	.901	.900	.898
1955	.895	.895	.893
1956	.921	.920	.918
1957	.911	.910	.907
1958	.906	.904	.900
1959	.901	.899	.896
1960	.912	.910	.906
1961	.927	.925	.922
1962	.935	.934	.931
1963	.956	.955	.952
1964	.958	.957	.954
1965	.989	.988	.986
1966	1.001	.999	.997
1967	1.009	1.007	1.005
1968	1.000	.998	.995
1969	1.009	1.007	1.005
1970	1.026	1.025	1.022
1971	1.012	1.010	1.006
1972	1.000	1.000	1.000
1973	1.020	1.021	1.024
1974	1.032	1.035	1.040
1975	1.002	1.009	1.022
1976	1.006	1.014	1.027
1977	1.024	1.032	1.045

Average Annual Growth Rates--Percent

1948-56	1.02	1.01	0.98
1956-67	0.83	0.82	0.83
1967-70	0.56	0.59	0.56
1967-73	0.18	0.23	0.31
1970-73	-0.20	-0.13	0.07
1970-77	-0.03	0.10	0.32
1973-77	0.10	0.27	0.51

early as 1970. This also implies that for countries like Japan with a younger and more energy-efficient capital stock in place by 1973, the capital measurement error may not be as severe. Hence international comparisons of productivity growth since 1973 using traditional capital stock measurement procedures should be carefully interpreted.

Before leaving this section, it is useful to comment briefly on implications of this analysis for labor (rather than multifactor) productivity growth. Rearrangement of (37) yields

$$(40) \qquad \frac{\dot{Y}}{Y} - \frac{\dot{L}}{L} = \frac{\dot{A}}{A} + \bar{S}_K \left(\frac{\dot{K}}{K} - \frac{\dot{L}}{L}\right) + \bar{S}_E\left(\frac{\dot{E}}{E} - \frac{\dot{L}}{L}\right) + \bar{S}_M \left(\frac{\dot{M}}{M} - \frac{\dot{L}}{L}\right) .$$

One clear implication of (40) is that measured average labor productivity growth is unaffected by changes in the measurement of quality-adjusted capital. However, since by (40) growth in labor productivity is an increasing function both of growth in multifactor productivity and in growth of the share-weighted capital-labor ratio, it follows that analysis of factors contributing to changes in labor productivity growth is affected by how one measures $\dot{A}/A$ and $(\dot{K}/K - \dot{L}/L)$. In the previous paragraph we discussed effects of energy price changes on $\dot{A}^*/A^*$; we now briefly examine traditional versus quality-adjusted growth in the capital-labor ratio.

In the top panel of Table 7 we present levels of the capital-labor ratio that are (i) traditionally measured; (ii) quality-adjusted based on NIPA *ex post* rate of return data, and (iii) quality-adjusted based on MARVAL *ex post* rate of return data. In the bottom panel we present average annual growth rates (AAGR) for selected subperiods.

Traditionally measured, the AAGR of the capital-labor ratio was 1.72 percent (1948-56), 0.79 percent (1956-67), 2.04 percent (1967-73) and 2.84

Table 7

Traditional and Quality-Adjusted Capital-Labor Ratios Based on NIPA and MARVAL-based Estimates of b_{KE}

U.S. Manufacturing, 1947-77

Year	K/L-traditional	K*/L--NIPA	K*/L--MARVAL
1947	.1535	.1557	.1596
1948	.1811	.1775	.1709
1949	.2130	.2169	.2242
1950	.2022	.2059	.2129
1951	.1900	.1969	.2100
1952	.1929	.1985	.2090
1953	.1910	.1967	.2074
1954	.2118	.2162	.2244
1955	.2073	.2120	.2210
1956	.2075	.2145	.2278
1957	.2188	.2280	.2460
1958	.2447	.2534	.2716
1959	.2311	.2412	.2607
1960	.2283	.2370	.2540
1961	.2338	.2417	.2569
1962	.2225	.2294	.2426
1963	.2234	.2309	.2453
1964	.2209	.2258	.2351
1965	.2171	.2227	.2333
1966	.2138	.2198	.2311
1967	.2264	.2340	.2485
1968	.2365	.2425	.2540
1969	.2420	.2485	.2609
1970	.2650	.2746	.2929
1971	.2794	.2822	.2873
1972	.2692	.2673	.2638
1973	.2555	.2485	.2362
1974	.2677	.2475	.2146
1975	.3020	.2784	.2399
1976	.2902	.2682	.2322
1977	.2858	.2619	.2232
Average Annual Growth Rates			
1948-56	1.72	2.40	3.66
1956-67	0.79	0.79	0.74
1967-70	5.39	5.48	5.64
1967-73	2.04	1.01	-0.85
1970-73	-1.22	-3.38	-7.43
1970-77	1.09	-0.68	-3.96
1973-77	2.84	1.32	-1.43

percent (1973-77). Hence, based on traditional measurement procedures, the 1973-77 period appears conducive to growth in labor productivity. However, if one quality-adjusts the capital data for energy price changes and uses the NIPA *ex post* rate of return data, while the AAGR over 1956-67 are unaffected, in 1967-73 and 1973-79 the AAGR fall to less than half their traditionally measured growth rates, 1.01 percent and 1.32 percent, respectively; using the securities' market MARVAL *ex post* rate of return, these growth rates actually become negative, i.e., -0.85 (1967-73) and -1.43 (1973-77).

We conclude, therefore, that quality-adjusted growth in the capital-labor ratio since 1973 appears to be considerably less than that based on traditional capital accounting procedures. This may help to "explain" the slowdown in labor productivity growth since 1973. Moreover, while the traditionally measured capital-labor ratio reaches its maximum value in 1975, the quality-adjusted capital-labor ratios attain their highest values in 1970 (MARVAL) or 1971 (NIPA), and decline thereafter. Whether these quality-adjusted capital-labor ratios help "explain" the post-1970 decline in the growth of real wages is an empirical hypothesis worthy of further examination.

VII. CONCLUDING REMARKS

For some time now observers have noted that the energy price increases of 1973-74 coincided with apparent reductions in productivity growth not only in the U.S. but also throughout most of the industrialized world. Precisely why energy price increases coincided with such developments has turned out to be an unresolved and important issue. Moreover, this issue of energy-economy interactions is apparently not confined to 1973-74. For example, Hamilton [1983] has recently provided time series evidence that suggests that a number of recessions in the U.S. since 1950 were each preceded by crude oil price increases. While Hamilton concludes that this relation is more than coincidental and instead appears to be systematic, he does not conjecture on the nature of the economic structure underlying this time series evidence.

The principal purpose of this paper has been to illuminate such issues by developing a methodology and then empirically implementing a procedure by which one can estimate the effects of energy price variations over time on the quality and economic value of the energy-using durable capital stock in U.S. manufacturing 1947-77. The framework we have employed is based on the modern theory of cost and production, and thus is consistent with observed factor demands in the manufacturing sector. The specification of the shadow cost relationship also ensures consistency with either the *ex post* rate of return on physical capital, or with the *ex post* return on financial capital. A principal conclusion of this research is that by 1977, traditional capital stock accounting measurement procedures overstated the quality-adjusted capital stock in U.S. manufacturing by between about 8 and 22 percent. This suggests that our results are empirically very significant.

In examining the effects of capital mismeasurement on traditionally measured multifactor productivity growth, we have found that the post-1973 productivity slowdown in the manufacturing sector has been substantially overestimated. Hence we find that energy is more important than its cost share would indicate. Moreover, it is worth noting here that this interpretation of factors "causing" the traditionally measured productivity slowdown has the advantage of being consistent with a number of recent seemingly paradoxical empirical factors, including:

i) the 1973 productivity growth slowdown appeared to be sudden rather than gradual. In our framework, the sharpness of the slowdown occured because much of the capital stock is fixed in the short-run, and was rendered economically less efficient by the sharp energy price increases;[15]

ii) in spite of the substantial post-1973 increases in the real price of energy, actual energy conservation since 1973 has been modest, suggesting that energy conservation cannot be named as a principal villain in the productivity growth slowdown. In our framework, it is precisely the lack of any short-run energy-capital substitutability relative to the long run that brings about the reduction in the economic value of the existing capital plant and equipment;[16]

iii) the energy cost share is relatively small, and thus the arithmetic of traditional multifactor productivity measurement--see (37)--prohibits energy price changes from having a substantial impact on measured multifactor productivity growth. In our framework, the effects of energy price changes are not confined to the energy cost share, but instead spill over to the measurement of capital. Hence energy price changes can have a much larger impact than its cost share would indicate;

iv) post-1973 investment in the U.S. manufacturing sector has been surprisingly strong[17], even though Tobin's q has been below unity. Such activity can be viewed as a rational attempt by manufacturing firms to replace their energy-inefficient capital stock with more fuel-efficient capital, i.e. the energy use characteristics of new investment goods could be much different from that embodied in the existing stock.

v) not much evidence is available yet on whether the physical scrapping of physical capital goods has accelerated since 1973. It should be noted that in order for the "capital decimation" hypothesis of our framework to be valid, it is not necessary that recent data reveal accelerated physical scrapping of durable capital goods. For example, old "gas guzzler" autos may still be running (perhaps at lower rates of utilization), yet it is known that their economic value depreciated rapidly after the 1973-74 and 1979-80 oil price increases. Physical and economic notions of capital are distinct, and the framework of this paper is compatible with such a distinction.

The procedures and results of this paper suggest a number of extensions for future research. First, the construction of the EEIR index implicitly assumes myopic expectations on relative energy prices. Although the underlying relative energy price data have a very smooth and simple time path suggesting that in this case empirical differences between myopic and nonstatic expectations formulations would be relatively minor, we believe it important to examine such expectations issues in greater detail. A related research issue concerns the specification of a dynamic model of investment that includes explicit consideration of the optimal energy efficiency of vintage-specific capital equipment.[18] One possible procedure would be to specify price-weighting each vintage of capital by the same exponential; see Appendix B for initial efforts in this direction.

Finally, the principal empirical results here revealing substantial price-induced economic depreciation of durable capital goods in U.S. manufacturing need to be estimated and validated further empirically--by examining industries at the more disaggregated level of detail, and by focussing on individual assets for which adequate leasing or second-hand markets exist, e.g. trucks, autos, tractors, airplanes, small boilers and ships.

Footnotes

1. See Muellbauer [1975] for quality specifications in the context of utility functions; also see Hall [1968] and especially Lau [1982].

2. In order to make use of the conversion formula (2), one needs to know y. Yet y is also on the left-hand side of (4). As Lau points out, however, it is still possible to determine y by solving (4) as an implicit function in y for given x, b and t.

3. See Lau [1982], p. 182.

4. Ibid.

5. Muellbauer calls this the variable repackaging hypothesis. For further discussion, see Berndt [1983b].

6. It is worth emphasizing here that recent econometric studies of the used automobile market by Kahn [1982], Daly-Mayor [1983] and Ohta-Griliches [1983] suggest quite clearly that the more general price-dependent hedonic specification (19) is preferable to that of (18), for not only do automobile prices depend on engineering design and performance characteristics, but they also depend on the price of gasoline.

7. For further discussion and an empirical implementation involving the translog variable on short-run cost function, see Brown-Christensen [1981].

8. Similar splicing of the M, P_M, and Y data is done using Berndt-Wood [1971] and Norsworthy-Harper [1981]; the Land P_L data is updated from Berndt-Wood [1975], and is described in Berndt-Morrision [1979] and Berndt [1980]. See also Morrison [1982] for additional details.

9. For further discussion, see Tobin [1969] and Holland-Myers [1979, 1980].

10. Estimation was undertaken using TSP Version 3.5 on the Harvard Science Center VAX.

11. The Wald-type t-statistic on b_{KE} with the MARVAL data (61.59) can be viewed as rather large; if, however, a likelihood ratio type t-test were used, the resulting asymptotic t-statistic would be 4.58.

12. A number of runs were also undertaken to assess the sensitivity of the b_{KE} estimates to the choice of four alternative EEIR indexes discussed in the data appendix; parameter estimates of b_{KE} varied less than 1% under these four different cases. Also, we have not yet checked whether these results are compatible with the required curvative conditions.

13. See Diewert [1976] for links between productivity formulation and the specification of cost or production functions.

14. In a different context, already in 1951 Lester Chandler argued that the value of much of the U.S. capital stock after 1945 had depreciated very rapidly due to changes in relative prices. Berndt first encountered the energy price increase-induced depreciation hypothesis in an informal conversation with W. Erwin Diewert and Jean Waelbroeck in 1974. The 1977 *Economic Report of the President* (p. 55) and Martin N. Baily [1981a,b] have raised the issue, as have Gregory [1980], Berndt [1982a,b] Schworm [1982], and undoubtedly others. In fact, energy price-induced economic depreciation of durable capital is an example of the analytical arguments presented in Feldstein-Rothschild [1974].

15. This "suddenness" does not appear to be supportive of the Jorgenson-Fraumeni [1981] biased tecnical change hypothesis, which is more long-run in nature.

16. For discussion of these points, see Denison [1979], Perry [1977], Manne-Hogan [1977], Wood [1982], and Berndt [1982a,b].

17. The strength of post-1973 investment in this sector provides little support for the Berndt-Wood long-run energy-capital complementarity hypothesis. For evidence on the strength of post-1973 investment, see Berndt [1980] and Bosworth [1982, including discussion].

18. For a survey of dynamic models, see Berndt, Morrison and Watkins [1981]; nonstatic expectations in structural dynamic investment models have recently been developed by Morrison [1982].

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APPENDIX A

DATA DEVELOPMENT FOR U.S. MANUFACTURING ENERGY PRICE AND QUANTITY SERIES, 1906-1947

by

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July 1983

Introduction

In this data appendix details are provided concerning the construction of coal (anthracite and bituminous), crude oil and oil products, natural gas and electricity price and quantity data series for total U.S. manufacturing, 1906-47. In addition, these components are aggregated into Divisia and Btu total energy and price indexes. Tables are also presented.

Briefly, for anthracite and bituminous coal, quantity data are based on various *Census of Manufactures* and the historical study by Schurr-Netschert [1960]; price data from Schurr-Netschert are f.o.b. mine prices. For crude oil and oil products, price and quantity data are taken from the same sources; price data here are average value per barrel at the well. For natural gas, a combination of data from the Census, Schurr-Netschert and *Historical Statistics of the United States: Colonial Times to 1970* is employed; price data represent delivered natural gas prices. Finally, for electricity the quantity series refers to consumption of purchased plus non-thermal self-generated electricity, since the primary fuels used to self-generate electricity via thermal methods are already included in the series on coal, crude oil and natural gas. Data for the electricity series are based on Census sources, Schurr-Netschert, and the Edison Electric Institute [1973].

Coal

Annual aggregate national consumption data on anthracite and bituminous coal (in millions of net tons) for the time period 1906-1947 are taken from Schurr-Netschert [1960, Appendix Table VI, columns 1 and 2, pp. 508-509]. Census data for the census years 1909, 1914, 1919, 1923, 1927, 1929, 1937, 1939 and 1947 covering the manufacturing industries are summarized in the 1947 Census of Manufactures Vol. 1, p. 203. Manufacturing coal consumption based on this census data as a percentage of the Schurr-Netschert national aggregate data are reported in Table A-1 below, where it is seen that the shares are reasonably stable over time, with some relatively minor cyclical variations.

Table A-1

Census Manufacturing Consumption as a Percentage of
Schurr-Netschert National Aggregate Coal
Consumption - Census Years

	1909	1914	1919	1923	1927	1929	1937	1939	1947
Bituminous Coal	40.88	37.91	42.33	n.a.	n.a.	37.87	37.83	36.74	38.49
Anthracite Coal	18.58	16.23	16.51	n.a.	n.a.	13.23	13.02	10.40	18.22
Sum	37.00	34.12	38.27	36.78	34.76	34.89	35.23	33.67	36.85

Key: n.a. denotes not available

The ratios of manufacturing to national coal consumption are interpolated between census years and extrapolated back to 1906, separately for bituminous and anthracite coal; this proportion is then applied to the Schurr-Netschert annual data, 1906-1947, to yield annual coal consumption quantity data for the manufacturing sector. The interpolation between the 1919 and 1929 census years is done so as to preserve the census anthracite-bituminous sums in 1923 and 1927. Note also that these quantity series include coal used for coke and the industrial generation of electricity within manufacturing.

The price series on anthracite and bituminous coal represent f.o.b. mine prices, and can be taken from Schurr-Netschert [1960, Appendix Table XXIII, columns 1 and 4, pp. 545-546], which in turn are based on various issues of the Minerals Yearbook. Alternatively, the price series can be computed as the value of coal consumption in current dollars, from Schurr-Netschert [1960, Table XVI, columns 1 and 2, pp. 532-533] divided by the Schurr-Netschert coal quantity series mentioned in the previous paragraph. The latter procedure was adopted here. The expenditure on coal is calculated as the price of coal (in current dollars per ton) times the manufacturing quantity consumption of coal, in millions of tons. The price (PCOALBM, PCOALAM), quantity (QCOALBM, QCOALAM) and expenditure (PQCOALBM, PQCOALAM, in millions of current dollars) data series for the years 1906-47 are presented in Tables A-2 and A-3.

Crude Oil

Annual aggregate national consumption data on crude oil and oil products (in millions of barrels) for the time period 1906-1947 are taken from Schurr-Netschert [1969, Appendix Table VI, column 3, pp. 508-9]. Census data for the census years 1909, 1914, 1919, 1929, 1937, 1939 and 1947 are summarized in the 1947 Census of Manufacturers, Vol. 1, p. 203. Manufacturing fuel oils consumption based on this census data as a percentage of the Schurr-Netschert national aggregate data are reported in Table A-4 below, where it is seen that the percentage rises to a peak in 1919, falls steadily to 1939, and changes only slightly by 1947. Given these time trends, the

Table A-4

Census Manufacturing Consumption as a Percentage of Schurr-Netschert National Aggregate Crude Oil Consumption - Census Years

	1909	1914	1919	1929	1937	1939	1947
Percentage	13.56	14.35	18.71	14.54	12.00	11.34	11.61

Table A-2

Price, Quantity and Expenditure for

Bituminous Coal, U.S. Manufacturing, 1906-47

YEAR	PCOALBM	QCOALBM	PQCOALBM
1906.00	1.11143	143.913	159.949
1907.00	1.14113	162.324	185.232
1908.00	1.11866	134.385	150.332
1909.00	1.07122	151.123	161.886
1910.00	1.11895	163.701	183.172
1911.00	1.10993	155.042	172.085
1912.00	1.14890	169.933	195.236
1913.00	1.17998	176.733	208.541
1914.00	1.17015	154.847	181.195
1915.00	1.12947	164.592	185.902
1916.00	1.31919	190.785	251.682
1917.00	2.25916	213.621	482.604
1918.00	2.58083	230.367	594.538
1919.00	2.49040	188.836	470.277
1920.00	3.74955	212.801	797.907
1921.00	2.88887	162.055	468.155
1922.00	3.01934	174.536	526.983
1923.00	2.68019	209.779	562.248
1924.00	2.20040	193.447	425.660
1925.00	2.03929	197.388	402.532
1926.00	2.05978	208.284	429.019
1927.00	1.99079	193.347	384.914
1928.00	1.86036	190.902	355.147
1929.00	1.78037	196.780	350.341
1930.00	1.69894	172.345	292.804
1931.00	1.54087	140.859	217.045
1932.00	1.30980	116.212	152.215
1933.00	1.34095	120.292	161.306
1934.00	1.75095	130.183	227.943
1935.00	1.77085	134.870	238.835
1936.00	1.76099	154.539	272.142
1937.00	1.94068	162.988	316.307
1938.00	1.95075	125.384	244.593
1939.00	1.83995	138.170	254.225
1940.00	1.90991	159.184	304.027
1941.00	2.19054	182.874	400.594
1942.00	2.36089	201.812	476.456
1943.00	2.68947	223.232	600.376
1944.00	2.92063	222.910	651.037
1945.00	3.05951	212.763	650.950
1946.00	3.43934	191.425	658.377
1947.00	4.16017	210.140	874.218

Table A-3

Price, Quantity and Expenditure for Anthracite Coal, U.S. Manufacturing, 1906-47

YEAR	PCOALAM	QCOALAM	PQCOALAM
1906.00	1.84496	14.0050	25.8387
1907.00	1.91297	16.2880	31.1585
1908.00	1.89514	15.3440	29.0791
1909.00	1.83592	14.4700	26.5658
1910.00	1.89866	14.6430	27.8020
1911.00	1.94251	15.1860	29.4990
1912.00	2.10639	13.7130	28.8849
1913.00	2.12955	14.4620	30.7975
1914.00	2.06810	14.0450	29.0464
1915.00	2.06978	13.8470	28.6603
1916.00	2.31551	13.5490	31.3729
1917.00	2.85205	15.3520	43.7846
1918.00	3.39738	15.4510	52.4929
1919.00	4.13472	13.7400	56.8110
1920.00	4.84928	13.8250	67.0412
1921.00	5.00305	12.8930	64.5043
1922.00	5.01769	8.73000	43.8045
1923.00	5.43066	12.7680	69.3386
1924.00	5.42637	11.8580	64.3458
1925.00	5.30744	9.20700	48.8656
1926.00	5.62023	10.8650	61.0638
1927.00	5.26302	10.2870	54.1407
1928.00	5.21385	9.91100	51.6745
1929.00	5.21992	9.45200	49.3387
1930.00	5.11622	8.92800	45.6777
1931.00	4.96507	7.69500	38.2062
1932.00	4.45545	6.64000	29.5842
1933.00	4.17339	6.50900	27.1646
1934.00	4.27027	7.26900	31.0406
1935.00	4.03131	6.68000	26.9292
1936.00	4.15414	6.94100	28.8339
1937.00	3.80952	6.56200	24.9981
1938.00	3.91593	5.22600	20.4646
1939.00	3.64185	5.16800	18.8211
1940.00	4.00000	5.38400	21.5360
1941.00	4.26945	6.13900	26.2102
1942.00	4.49558	7.00200	31.4780
1943.00	5.06130	7.56000	38.2634
1944.00	5.57239	8.44100	47.0365
1945.00	5.89147	7.91300	46.6192
1946.00	6.82746	8.97600	61.2833
1947.00	7.21992	8.78100	63.3981

ratios of manufacturing to national crude oil consumption are interpolated between census years 1909-1947 and extrapolated from 1909 back to 1906; this proportion is then applied to the Schurr-Netschert annual data, 1906-47, to yield annual coal consumption quantity data for the manufacturing sector. Note also that this quantity series (denoted QOILCM, in millions of barrels) includes oil and petroleum products used for coke and the industrial generation of electricity within manufacturing.

The price series on crude oil and oil products represents average value per barrel at well in current dollars, and can be taken from Schurr-Netschert [1960, Appendix Table XXIV, column 1, pp. 546-8] which in turn is based on various issues of the Minerals Yearbook. Alternatively, the price series can be calculated as the value of crude oil and oil products consumption, from Schurr-Netschert [1960, Appendix Table XVI, column 4, pp. 532-3] divided by the Schurr-Netschert crude oil and oil product quantity consumption series mentioned in the previous paragraph. The latter procedure was employed here. Expenditure on crude oil and oil products is calculated as the price of crude oil and oil products (in current dollars per ton, denoted POILCM) times the corresponding manufacturing consumption in millions of barrels, QOILCM; the resulting product represents the value of crude oil and oil product consumption in the manufacturing sector in millions of current dollars, and is denoted PQOILCM. These quantity, price and value data series for the 1906-47 time period are presented in Table A-5.

Natural Gas

Annual aggregate national consumption data on dry natural gas (in billions of cubic feet) for the time period 1906-47 are taken from

TABLE A-5

Price, Quantity and Expenditure for Crude Oil and Oil Products, U.S. Manufacturing, 1906-47

YEAR	POILCM	QOILCM	PQOILCM
1906.00	0.731460	12.5660	9.19153
1907.00	0.720188	17.8750	12.8734
1908.00	0.721516	18.9660	13.6843
1909.00	0.701286	19.7270	13.8343
1910.00	0.610743	23.8010	14.5363
1911.00	0.607818	24.8690	15.1158
1912.00	0.739921	25.5890	18.9338
1913.00	0.948817	29.6040	28.0888
1914.00	0.808272	32.6700	26.4063
1915.00	0.641368	36.6090	23.4799
1916.00	1.10064	40.8340	44.9437
1917.00	1.55958	55.0760	85.8956
1918.00	1.97892	58.1080	114.991
1919.00	2.00927	69.6390	139.924
1920.00	3.07105	82.6040	253.681
1921.00	1.72934	81.6430	141.189
1922.00	1.61043	91.2440	146.942
1923.00	1.33977	108.865	145.854
1924.00	1.43010	105.843	151.366
1925.00	1.67994	114.319	192.049
1926.00	1.88030	116.112	218.326
1927.00	1.30049	114.815	149.316
1928.00	1.17009	121.910	142.645
1929.00	1.27028	132.221	167.958
1930.00	1.18979	137.521	163.621
1931.00	0.649532	118.003	76.6467
1932.00	0.870209	106.199	92.4154
1933.00	0.670233	109.474	73.3731
1934.00	1.00033	106.424	106.459
1935.00	0.969491	118.692	115.071
1936.00	1.08958	129.263	140.842
1937.00	1.18036	136.255	160.830
1938.00	1.12986	129.535	146.356
1939.00	1.01995	133.404	136.065
1940.00	1.02027	146.117	149.079
1941.00	1.13975	161.091	183.604
1942.00	1.18966	150.865	179.478
1943.00	1.20028	162.398	194.923
1944.00	1.20992	182.515	220.828
1945.00	1.21999	191.769	233.957
1946.00	1.40996	198.616	280.041
1947.00	1.93008	215.559	416.046

Schurr-Netschert [1960, Appendix Table VI, column 5, pp. 508-9]. Census manufacturing data on total gas product consumption (dry natural gas plus manufactured gas and mixed gas) are available for the census years 1909, 1914, 1919, 1929, 1939, 1947 and 1954, but unfortunately, the compositional breakdown into dry natural gas (consistent with the Schurr-Netschert series), manufactured and mixed gas is available only for the census years 1929, 1939 and 1947, at which time dry natural gas accounted for 30.99%, 34.92%, and 32.20% of total manufacturing natural gas consumption, respectively.

Data on industrial dry natural gas consumption annually for the years 1922-70 are available, however, from the Bicentennial Edition of the U.S. Department of Commerce, Bureau of the Census publication Historical Statistics of the United States: Colonial Times to 1970, Part 2, Series S 176-189, column 179, p. 831; the corresponding average price per thousand cubic foot is found in column 187 of the same table.

In order to extend the quantity series backward from 1922 to 1906, industrial dry natural gas consumption figures for 1906, 1910, 1915, 1929 and 1925 are taken from Schurr-Netschert [1960, Table 41, column 4, p. 133], and are compared to figures for aggregate national consumption based on Schurr-Netschert [1960, Appendix Table VI, column 5, pp. 508-9]; the proportions are 72.77% (1906), 67.53 (1910), 65.65 (1915), 62.51 (1920), and 79.63 (1925). These ratios are interpolated for industrial dry natural gas consumption over the entire 1906-47 time period.

Census manufacturing dry natural gas consumption as a proportion of this industrial dry natural gas consumption can be calculated from the 1947 Census of Manufactures, Volume 1, p. 203, and turn out to be 43.27% in 1929, 49.90% in 1939, and 51.59% in 1947. For the census year 1937, one can interpolate the dry over total manufacturing gas product consumption between 1929 and 1939 (see the first paragraph of this section) and arrive at a 1937 figure for manufacturing over industrial dry gas consumption equal to 49.73%. By holding the proportion over the 1906-1929 time period equal to its 1929 value (43.27%), interpolating linearly between 1929, 1937, 1939 and 1947, and then multiplying the proportion times the industrial dry natural consumption, one obtains a quantity series on annual manufacturing dry natural gas consumption. The resulting quantity series is denoted QNGASDM, and is in billions of cubic feet. Note that these quantity figures include some natural gas used for the industrial generation of electricity.

The price series on industrial dry natural gas consumption, as noted above, is available for the 1922-70 time period. To extend this price series back to 1906, the average price at the well for total national consumption 1906-21 is taken from Schurr-Netschert [1960, Appendix Table XVI, column 5, pp. 532-3 divided by entries in Table VI, column 5, pp. 508-9]. The Historical Statistics of the United States: Colonial Times to the Present value for average prices [Part 2, Series S 176-189, column 187, p. 831] is divided by the above Schurr-Netschert index for the years 1923-27; since this ratio is relatively constant at about 1.35, the Schurr-Netschert series is multiplied by 1.35 during the 1906-21 time period, thereby yielding a price series for manufacturing dry natural gas consumption in dollars per cubic foot; this series is denoted as PGASDRYM.

Expenditure on dry natural gas consumption for the manufacturing sector is then computed as price times quantity, is denoted as PQNGASDM, and is in units of millions of current dollars.

The three series QNGASDM, PGASDRYM, and PQNGASDM are tabulated in Table A-6.

Table A-6

Price, Quantity and Expenditure for Natural Gas, U.S. Manufacturing, 1906-47

YEAR	PGASDRYM	QNGASDM	PQNGASDM
1906.00	0.640000E-01	251.813	16.1160
1907.00	0.710000E-01	263.780	18.7284
1908.00	0.710000E-01	259.308	18.4109
1909.00	0.680000E-01	308.843	21.0013
1910.00	0.730000E-01	325.130	23.7345
1911.00	0.750000E-01	326.452	24.4839
1912.00	0.780000E-01	355.170	27.7033
1913.00	0.770000E-01	368.926	28.4073
1914.00	0.830000E-01	373.695	31.0167
1915.00	0.820000E-01	412.657	33.8379
1916.00	0.830000E-01	512.645	42.5495
1917.00	0.920000E-01	560.284	51.5461
1918.00	0.109000	528.371	57.5924
1919.00	0.112000	565.797	63.3693
1920.00	0.127000	542.585	68.9083
1921.00	0.136000	406.762	55.3196
1922.00	0.186000	430.088	79.9964
1923.00	0.134000	521.979	69.9452
1924.00	0.116000	549.661	63.7607
1925.00	0.123000	532.032	65.4399
1926.00	0.128000	549.534	70.3404
1927.00	0.120000	567.661	68.1193
1928.00	0.132000	581.421	76.7476
1929.00	0.122000	673.765	82.1993
1930.00	0.113000	690.530	78.0299
1931.00	0.109000	606.567	66.1158
1932.00	0.100000	568.264	56.8264
1933.00	0.980000E-01	575.571	56.4060
1934.00	0.970000E-01	662.591	64.2713
1935.00	0.970000E-01	725.514	70.3749
1936.00	0.100000	831.138	83.1138
1937.00	0.103000	935.054	96.3106
1938.00	0.940000E-01	900.186	84.6175
1939.00	0.960000E-01	980.515	94.1294
1940.00	0.950000E-01	1054.95	100.220
1941.00	0.105000	1100.54	115.557
1942.00	0.109000	1196.15	130.380
1943.00	0.113000	1340.01	151.421
1944.00	0.108000	1449.26	156.521
1945.00	0.105000	1523.64	159.982
1946.00	0.107000	1566.00	167.562
1947.00	0.113000	1723.19	194.721

Electricity

The data on electricity consumption for the manufacturing sector present special problems, for not only has electricity been purchased from utilities, but it has also been self-generated by hydro and thermal methods within manufacturing industries. Since the data on coal, fuel oil and natural gas already include consumption for the purpose of electricity self-generation by manufacturing industries, it is necessary to develop an electricity quantity consumption series net of non-hydro self-generated electricity. On the price side, the hydro-generated electricity will be valued equal to the unit price of purchased electricity by manufacturing industries.

Total manufacturing consumption of electricity for 1912, 1917, and annually since 1920 are taken from the Bicentennial Edition of Historical Statistics of the United States: Colonial Times to 1970, Part II, Series S120-132, column 124, p. 828. To obtain an estimate of manufacturing hydro self-generation, the industrial non-hydro self-generation figures from the Bicentennial Edition of Historical Statistics of the United States: Colonial Times to 1970, Part II, Series S32-43, column 40, minus column 41, p. 820 are multiplied by the ratio of manufacturing (Series S120-132, column 124, p. 828) to total industrial (series S120-32, column 123, p. 828) electricity consumption for the years 1912, 1917, and annually since 1920. These figures are interpolated between 1912, 1917, and 1920, and extrapolated back to 1906. Given this manufacturing series on non-hydro self-generated electricity for manufacturing, it is subtracted from total manufacturing electricity consumption (see first sentence of this paragraph) to yield a series on manufacturing consumption of electricity net of thermally self-generated electricity. This series is denoted as QELECM, and is in units of millions of kilowatt-hours.

To obtain a price series for electricity, data on revenues and sales by the electric utility industry to large light and power industrial customers are taken from the Edison Electric Institute [1973, Table 33, column 7, p. 88 and Table 19, column 7, p. 60] for the years 1926 onward, annually, to obtain an annual average price series for manufacturing customers, 1926 onward. The ratio of this average electricity price, incidentally, to the average price implicit in the 1929, 1937, 1939 and 1947 Census of Manufactures is 1.087, 1.116, 1.084 and 1.050, respectively; hence the two series are very close in their average price for electricity values.

To extend this Edison Electric Institute (EEI) price series back from 1926 to 1906, the residential average revenue per kwhr used for the 1906-27 time period is taken from EEI [1973, Table 61, column 1, p. 165]. The previously noted average industrial price for 1926-27 is divided by the corresponding residential price, yielding values of 3.354 (1927) and 3.360 (1926). The EEI residential average revenue series is then divided by 3.360 for all years 1960-25 to obtain the industrial average electricity price during this time interval. The resulting price series, in current dollars per kilowatt hour, is denoted as PELECM.

Expenditures on manufacturing electricity (assuming implicitly that self-generated hydro electricity is valuated at its purchased opportunity cost) is then calculated simply as the product of PELECM and QELECM, and is denoted as PQELECM, in millions of current dollars. These three series on manufacturing electricity consumption data are presented in Table A-7.

Table A-7

Price, Quantity and Expenditure for Electricity, U.S. Manufacturing, 1906-47

YEAR	PELECM	QELECM	PQELECM
1906.00	0.282700E-01	239.000	6.75653
1907.00	0.276800E-01	330.000	9.13440
1908.00	0.267900E-01	421.000	11.2786
1909.00	0.261900E-01	512.000	13.4093
1910.00	0.253000E-01	603.000	15.2559
1911.00	0.247000E-01	694.000	17.1418
1912.00	0.232100E-01	787.000	18.2663
1913.00	0.220200E-01	2309.00	50.8442
1914.00	0.217300E-01	3829.00	83.2042
1915.00	0.193500E-01	5349.00	103.503
1916.00	0.175600E-01	6869.00	120.620
1917.00	0.172600E-01	8389.00	144.794
1918.00	0.166700E-01	10975.0	182.953
1919.00	0.166700E-01	13562.0	226.079
1920.00	0.172600E-01	16150.0	278.749
1921.00	0.169600E-01	13781.0	233.726
1922.00	0.169600E-01	16157.0	274.023
1923.00	0.160700E-01	19218.0	308.833
1924.00	0.154800E-01	20575.0	318.501
1925.00	0.148800E-01	23224.0	345.573
1926.00	0.148841E-01	28667.0	426.682
1927.00	0.146059E-01	31879.0	465.622
1928.00	0.140309E-01	34308.0	481.371
1929.00	0.137544E-01	37548.0	516.449
1930.00	0.141095E-01	36391.0	513.459
1931.00	0.147475E-01	33511.0	494.204
1932.00	0.153213E-01	28427.0	435.539
1933.00	0.138344E-01	30877.0	427.164
1934.00	0.135192E-01	32835.0	443.902
1935.00	0.129966E-01	38995.0	506.803
1936.00	0.119443E-01	42412.0	506.581
1937.00	0.113553E-01	44180.0	501.677
1938.00	0.120235E-01	37115.0	446.252
1939.00	0.112049E-01	44022.0	493.261
1940.00	0.106021E-01	52883.0	560.670
1941.00	0.996678E-02	68408.0	681.807
1942.00	0.937245E-02	84335.0	790.425
1943.00	0.904012E-02	102984.	930.988
1944.00	0.905824E-02	102024.	924.158
1945.00	0.932140E-02	94350.0	879.474
1946.00	0.980279E-02	87454.0	857.293
1947.00	0.974741E-02	101082.	985.288

Aggregation into Total Energy Index

The five energy types -- bituminous and anthracite coal, oil and oil products, natural gas and electricity can be aggregated using the Divisia index. The discrete approximation to the Divisia price index is

$$\ln (P_{Et}/P_{E,t-1}) = \sum_i \bar{w}_{it} \ln (P_{Ei,t}/P_{Ei,t-1})$$

where $\bar{w}_{it}$ is the arithmetic mean of the i^{th} energy type cost share in periods t and t-1,

$$\bar{w}_{it} = \frac{1}{2} (w_{it} + w_{i,t-1}) \quad ,$$

$$w_{it} = \frac{P_{Ei,t} E_{i,t}}{\Sigma P_{Ei,t}} \quad , \text{ i = bituminous coal, anthracite coal, oil, natural gas and electricity,}$$

where the i subscript on P_E or E denotes the price or quantity of the i^{th} energy type, respectively. Hence the percentage change in the Divisia aggregate energy price index between periods t and t-1 is a weighted average of the percentage change in each of the individual energy types, where the weights are the average cost shares. The implicit Divisia aggregate energy quantity index is then computed as total expenditure on energy divided by the aggregate energy price index.

The cost shares for electricity (SELEC), anthracite coal (SCOALA), bituminous coal (SCOALB), oil and oil products (SOILC) and natural gas (SGAS) for the 1906-47 time period are presented in Table A-8, while the Divisia aggregate price (PE), Divisia implicit aggregate energy quantity (QE) and total energy expenditure values (PQE, in millions of current dollars) are presented in Table A-9.

Table A-8

Cost Shares of Energy Types in Total U.S. Manufacturing, 1906-47

YEAR	SELEC	SCOALA	SCOALB	SOILC	SGAS
1906.00	0.310144E-01	0.118607	0.734210	0.421917E-01	0.739772E-01
1907.00	0.355249E-01	0.121180	0.720392	0.500662E-01	0.728372E-01
1908.00	0.506255E-01	0.130526	0.674785	0.614238E-01	0.826398E-01
1909.00	0.566519E-01	0.112236	0.683938	0.584474E-01	0.887269E-01
1910.00	0.576780E-01	0.105111	0.692520	0.549574E-01	0.897330E-01
1911.00	0.663573E-01	0.114193	0.666156	0.585146E-01	0.947792E-01
1912.00	0.631997E-01	0.999394E-01	0.675501	0.655094E-01	0.958508E-01
1913.00	0.146661	0.888357E-01	0.601540	0.810224E-01	0.819412E-01
1914.00	0.237138	0.827844E-01	0.516418	0.752597E-01	0.883997E-01
1915.00	0.275727	0.763495E-01	0.495232	0.625491E-01	0.901423E-01
1916.00	0.245577	0.638741E-01	0.512415	0.915037E-01	0.866294E-01
1917.00	0.179062	0.541470E-01	0.596821	0.106224	0.637454E-01
1918.00	0.182485	0.523584E-01	0.593015	0.114697	0.574450E-01
1919.00	0.236370	0.593971E-01	0.491685	0.146293	0.662540E-01
1920.00	0.190105	0.457218E-01	0.544169	0.173009	0.469951E-01
1921.00	0.242733	0.669901E-01	0.486196	0.146630	0.574514E-01
1922.00	0.255678	0.408720E-01	0.491704	0.137105	0.746410E-01
1923.00	0.267106	0.599701E-01	0.486281	0.126147	0.604948E-01
1924.00	0.311148	0.628603E-01	0.415832	0.147871	0.622886E-01
1925.00	0.327725	0.463419E-01	0.381742	0.182131	0.620602E-01
1926.00	0.353966	0.506572E-01	0.355905	0.181118	0.583528E-01
1927.00	0.414952	0.482489E-01	0.343026	0.133067	0.607064E-01
1928.00	0.434613	0.466551E-01	0.320650	0.128789	0.692927E-01
1929.00	0.442815	0.423041E-01	0.300390	0.144011	0.704795E-01
1930.00	0.469516	0.417685E-01	0.267745	0.149618	0.713520E-01
1931.00	0.553905	0.428217E-01	0.243264	0.859058E-01	0.741028E-01
1932.00	0.568159	0.385925E-01	0.198563	0.120556	0.741299E-01
1933.00	0.573056	0.364423E-01	0.216398	0.984328E-01	0.756707E-01
1934.00	0.508120	0.355312E-01	0.260919	0.121860	0.735693E-01
1935.00	0.529015	0.281094E-01	0.249302	0.120114	0.734592E-01
1936.00	0.491105	0.279530E-01	0.263828	0.136539	0.805747E-01
1937.00	0.456019	0.227230E-01	0.287520	0.146193	0.875452E-01
1938.00	0.473586	0.217181E-01	0.259575	0.155321	0.898005E-01
1939.00	0.494992	0.188871E-01	0.255118	0.136543	0.944598E-01
1940.00	0.493751	0.189656E-01	0.267740	0.131285	0.882584E-01
1941.00	0.484317	0.186182E-01	0.284559	0.130421	0.820850E-01
1942.00	0.491492	0.195732E-01	0.296264	0.111600	0.810711E-01
1943.00	0.485909	0.199708E-01	0.313353	0.101736	0.790312E-01
1944.00	0.462176	0.235232E-01	0.325587	0.110437	0.782767E-01
1945.00	0.446211	0.236528E-01	0.330267	0.118700	0.811689E-01
1946.00	0.423448	0.302700E-01	0.325195	0.138322	0.827647E-01
1947.00	0.388877	0.250222E-01	0.345040	0.164207	0.768532E-01

Table A-9

Divisia Aggregate Energy Price, Implicit Divisia Aggregate Energy Quantity Index and Total Energy Expenditure in U.S. Manufacturing, 1906-47

YEAR	PE	QE	PQE
1906.00	0.353918	615.541	217.851
1907.00	0.364595	705.239	257.127
1908.00	0.358682	621.120	222.785
1909.00	0.344647	686.779	236.696
1910.00	0.355203	744.648	264.501
1911.00	0.354401	728.909	258.326
1912.00	0.370242	780.638	289.025
1913.00	0.381373	909.028	346.679
1914.00	0.375370	934.727	350.868
1915.00	0.351888	1066.77	375.383
1916.00	0.390245	1258.61	491.167
1917.00	0.553345	1461.34	808.625
1918.00	0.623147	1608.88	1002.57
1919.00	0.620224	1542.12	956.460
1920.00	0.839373	1746.88	1466.29
1921.00	0.670531	1436.02	962.894
1922.00	0.692562	1547.51	1071.75
1923.00	0.617486	1872.46	1156.22
1924.00	0.558864	1831.63	1023.63
1925.00	0.551123	1913.29	1054.46
1926.00	0.567579	2123.81	1205.43
1927.00	0.521762	2150.62	1122.11
1928.00	0.497492	2226.34	1107.58
1929.00	0.489289	2383.64	1166.29
1930.00	0.480772	2274.66	1093.59
1931.00	0.444924	2005.33	892.217
1932.00	0.447118	1714.49	766.579
1933.00	0.410301	1816.75	745.413
1934.00	0.451362	1935.51	873.616
1935.00	0.441021	2172.26	958.013
1936.00	0.429561	2401.32	1031.51
1937.00	0.435810	2524.32	1100.12
1938.00	0.441912	2132.29	942.283
1939.00	0.414654	2403.21	996.502
1940.00	0.407778	2784.68	1135.53
1941.00	0.420988	3343.98	1407.77
1942.00	0.421397	3816.39	1608.22
1943.00	0.433472	4420.06	1915.97
1944.00	0.445189	4491.53	1999.58
1945.00	0.457949	4303.93	1970.98
1946.00	0.498262	4063.23	2024.56
1947.00	0.558909	4533.24	2533.67

An alternative way of aggregating is to convert each of the energy types into British thermal units (Btu's) and then sum over Btu's. As has been discussed by Berndt [1978], the Btu aggregation procedure implicitly assumes perfect substitutability among energy types, whereas the Divisia index places no prior restrictions on such substitution possibilities. Hence on grounds of basic economic reasoning, there is a clear preference for the Divisia index. Nonetheless, for purposes of comparison, the Btu aggregation procedure has also been employed.

Based on Schurr-Netschert [1960, Note to Appendix Table II, p. 499], Btu conversion rates are 26.2 million Btu per net ton of bituminous coal, 25.4 million Btu per net ton of anthracite coal, 5.8 million Btu per 42 gallon barrel of crude oil, and 1075 Btu per cubic foot of dry natural gas. For electricity, annual data on the heat rate for electricity generation in Btu per kilowatt hour are taken from the Edison Electric Institute [1973, Table 41, column 6, p. 115] covering the period since 1926. Schurr-Netschert [1960, note to Table II, p. 499] note that the heat rate in 1900 was 6.85 pounds of coal; the corresponding EEI figure for 1925 is 2.029 pounds of coal per kilowatt hour. This implies an annual average heat rate improvement over the 1900-1925 time period of 5% per year. Using this 5% figure, then, the electricity generation heat rate was extended from 1925 back to 1900. Incidentally, over the 1906-47 time period the heat rate improved from 63,616 to 15,600 Btu's pe kilowatt hour.

Using these Btu conversion ratios, the energy quantity data in physical units from earlier tables have been transformed into Btu measures. These data --BTUBIT (bituminous coal), BTUANTH (anthracite coal), BTUOIL (crude oil and oil products), BTUGAS (natural gas) and BTUELEC (electricity) -- all measured in trillions of Btu's -- are listed in Table A-10. The corresponding Btu shares (SHRBIT, SHRANTH, SHROIL, SHRELEC and SHRNGAS) are listed in Table A-11, while the aggregate sum of Btu's (BTUSUM) across energy types in

Table A-10

Quantities of Energy Types Consumed in U.S. Manufacturing, 1906-47--Trillions of Btu's

YEAR	BTUBIT	BTUANTH	BTUOIL	BTUGAS	BTUELEC
1906.00	3770.52	355.727	72.8828	270.699	15.2042
1907.00	4252.89	413.715	103.675	283.564	19.9937
1908.00	3520.89	389.738	110.003	278.756	24.2925
1909.00	3959.42	367.538	114.417	332.006	28.1364
1910.00	4288.97	371.932	138.046	349.515	31.5592
1911.00	4062.10	385.724	144.240	350.936	34.5924
1912.00	4452.24	348.310	148.416	381.808	37.3597
1913.00	4630.40	367.335	171.703	396.595	104.392
1914.00	4056.99	356.743	189.486	401.722	164.869
1915.00	4312.31	351.714	212.332	443.606	219.346
1916.00	4998.57	344.145	236.837	551.093	268.269
1917.00	5596.87	389.941	319.441	602.305	312.029
1918.00	6035.62	392.455	337.026	567.999	388.778
1919.00	4947.50	348.996	403.906	608.232	457.541
1920.00	5575.39	351.155	479.103	583.279	518.899
1921.00	4245.84	327.482	473.529	437.269	421.699
1922.00	4572.84	221.742	529.215	462.345	470.863
1923.00	5496.21	324.307	631.417	561.127	533.396
1924.00	5068.31	301.193	613.889	590.886	543.880
1925.00	5171.57	233.858	663.050	571.934	584.664
1926.00	5457.04	275.971	673.450	590.749	676.541
1927.00	5065.69	261.290	665.927	610.236	720.465
1928.00	5001.63	251.739	707.078	625.028	737.622
1929.00	5155.64	240.081	766.882	724.297	771.611
1930.00	4515.44	226.771	797.622	742.320	720.542
1931.00	3690.51	195.453	684.417	652.060	630.007
1932.00	3044.75	168.656	615.954	610.884	524.478
1933.00	3151.65	165.329	634.949	618.739	560.418
1934.00	3410.79	184.633	617.259	712.285	589.388
1935.00	3533.59	169.672	688.414	779.928	696.061
1936.00	4048.92	176.301	749.725	893.473	754.934
1937.00	4270.29	166.675	790.279	1005.18	788.613
1938.00	3285.06	132.740	751.303	967.700	647.657
1939.00	3620.05	131.267	773.743	1054.05	735.167
1940.00	4170.62	136.754	847.479	1134.07	867.281
1941.00	4791.30	155.931	934.328	1183.08	1132.15
1942.00	5287.47	177.851	875.017	1285.86	1357.79
1943.00	5848.68	192.024	941.908	1440.51	1647.74
1944.00	5840.24	214.401	1058.59	1557.96	1617.08
1945.00	5574.39	200.990	1112.26	1637.92	1490.73
1946.00	5015.34	227.990	1151.97	1683.45	1373.03
1947.00	5505.67	223.037	1250.24	1852.43	1576.88

Table A-11

Btu Quantity Shares of Energy Types

Consumed in U.S. Manufacturing, 1906-47

YEAR	SHRBIT	SHRANTH	SHROIL	SHRELEC	SHRNGAS
1906.00	0.840689	0.793142E-01	0.162502E-01	0.338999E-02	0.603561E-01
1907.00	0.838200	0.815389E-01	0.204333E-01	0.394055E-02	0.558874E-01
1908.00	0.814327	0.901403E-01	0.254420E-01	0.561849E-02	0.644720E-01
1909.00	0.824619	0.765462E-01	0.238292E-01	0.585990E-02	0.691461E-01
1910.00	0.827983	0.718013E-01	0.266497E-01	0.609249E-02	0.674737E-01
1911.00	0.816077	0.774921E-01	0.289779E-01	0.694963E-02	0.705031E-01
1912.00	0.829383	0.648847E-01	0.276476E-01	0.695952E-02	0.711248E-01
1913.00	0.816588	0.647808E-01	0.302805E-01	0.184099E-01	0.699410E-01
1914.00	0.784746	0.690050E-01	0.366524E-01	0.318907E-01	0.777054E-01
1915.00	0.778492	0.634942E-01	0.383319E-01	0.395982E-01	0.800833E-01
1916.00	0.781159	0.537817E-01	0.370121E-01	0.419241E-01	0.861230E-01
1917.00	0.775127	0.540040E-01	0.442403E-01	0.432138E-01	0.834150E-01
1918.00	0.781626	0.508238E-01	0.436457E-01	0.503477E-01	0.735571E-01
1919.00	0.731211	0.515795E-01	0.596949E-01	0.676218E-01	0.898930E-01
1920.00	0.742610	0.467719E-01	0.638139E-01	0.691145E-01	0.776895E-01
1921.00	0.718925	0.554508E-01	0.801801E-01	0.714039E-01	0.740404E-01
1922.00	0.730835	0.354390E-01	0.845796E-01	0.752538E-01	0.738923E-01
1923.00	0.728317	0.429748E-01	0.836707E-01	0.706816E-01	0.743564E-01
1924.00	0.712026	0.423134E-01	0.862427E-01	0.764073E-01	0.830110E-01
1925.00	0.715780	0.323675E-01	0.917707E-01	0.809216E-01	0.791597E-01
1926.00	0.711131	0.359630E-01	0.877602E-01	0.881630E-01	0.769831E-01
1927.00	0.691693	0.356777E-01	0.909288E-01	0.983757E-01	0.833244E-01
1928.00	0.682994	0.343761E-01	0.965545E-01	0.100725	0.853501E-01
1929.00	0.673191	0.313482E-01	0.100135	0.100752	0.945742E-01
1930.00	0.644815	0.323834E-01	0.113902	0.102895	0.106005
1931.00	0.630592	0.333968E-01	0.116946	0.107649	0.111417
1932.00	0.613277	0.339709E-01	0.124066	0.105641	0.123045
1933.00	0.614227	0.322210E-01	0.123746	0.109220	0.120586
1934.00	0.618530	0.334821E-01	0.111937	0.106882	0.129169
1935.00	0.602214	0.289164E-01	0.117323	0.118626	0.132920
1936.00	0.611310	0.266181E-01	0.113194	0.113981	0.134897
1937.00	0.608213	0.237393E-01	0.112559	0.112321	0.143167
1938.00	0.567911	0.229478E-01	0.129883	0.111965	0.167293
1939.00	0.573312	0.207889E-01	0.122539	0.116429	0.166932
1940.00	0.582798	0.191098E-01	0.118426	0.121193	0.158474
1941.00	0.584533	0.190234E-01	0.113987	0.138121	0.144335
1942.00	0.588544	0.197964E-01	0.973973E-01	0.151135	0.143128
1943.00	0.580752	0.190673E-01	0.935280E-01	0.163615	0.143038
1944.00	0.567660	0.208394E-01	0.102893	0.157177	0.151431
1945.00	0.556533	0.200663E-01	0.111045	0.148831	0.163525
1946.00	0.530624	0.241214E-01	0.121879	0.145267	0.178109
1947.00	0.528971	0.214289E-01	0.120120	0.151503	0.177977

trillions of Btu's as well as the corresponding price (in dollars per trillion Btu) are presented in Table A-12.

Note that according the the Btu index, over the 1906 time period the aggregate energy quantity increased 132% and the average price in current dollars increased 401%, for the Divisia energy index the figures are 636% (quantity) and 58%. Hence the two aggregation procedures yield rather different results.

Table A-12

Btu Aggregate Energy Quantity and Aggregate Energy Price, U.S. Manufacturing--Trillions of Btu's

YEAR	BTUSUM	PRICEBTU
1906.00	4485.03	0.485730E-01
1907.00	5073.84	0.506770E-01
1908.00	4323.68	0.515267E-01
1909.00	4801.52	0.492961E-01
1910.00	5180.02	0.510618E-01
1911.00	4977.59	0.518977E-01
1912.00	5368.14	0.538408E-01
1913.00	5670.43	0.611381E-01
1914.00	5169.81	0.678687E-01
1915.00	5539.31	0.677671E-01
1916.00	6398.91	0.767580E-01
1917.00	7220.59	0.111989
1918.00	7721.88	0.129835
1919.00	6766.18	0.141359
1920.00	7507.82	0.195301
1921.00	5905.82	0.163042
1922.00	6257.01	0.171288
1923.00	7546.46	0.153213
1924.00	7118.16	0.143806
1925.00	7225.07	0.145944
1926.00	7673.75	0.157085
1927.00	7323.61	0.153218
1928.00	7323.10	0.151245
1929.00	7658.51	0.152286
1930.00	7002.69	0.156167
1931.00	5852.44	0.152452
1932.00	4964.73	0.154405
1933.00	5131.08	0.145274
1934.00	5514.36	0.158426
1935.00	5867.67	0.163270
1936.00	6623.36	0.155739
1937.00	7021.04	0.156690
1938.00	5784.46	0.162899
1939.00	6314.29	0.157817
1940.00	7156.21	0.158678
1941.00	8196.79	0.171747
1942.00	8983.99	0.179009
1943.00	10070.9	0.190249
1944.00	10288.3	0.194355
1945.00	10016.3	0.196778
1946.00	9451.77	0.214199
1947.00	10408.3	0.243429

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APPENDIX B

DATA CONSTRUCTION PROCEDURES AND SOURCES FOR THE DEVELOPMENT OF ENERGY EFFICIENCY MEASURES OF THE FIXED CAPITAL STOCK IN U.S. MANUFACTURING, 1947-77

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INTRODUCTION

In this data appendix, details are provided on procedures and sources employed in the construction of the embodied energy inefficiency ratio (hereafter, EEIR) for the fixed capital stock in U.S. manufacturing, 1947-77. The first portion of the appendix briefly outlines theoretical considerations, the second summarizes data sources for the 1906-77 time period necessary for the vintage-specific data construction, and the final portion discusses alternative weighting choices employed for equipment and structure. A number of data tables are also listed.

THEORETICAL CONSIDERATIONS

We begin by describing the investment choices open to firms. Assume that at time $t-\tau$, firms have decided on the amount and durability of investment they wish to undertake, based on, for example, expected output demand and labor costs, and now must choose the optimal energy efficiency of this new equipment or structure. This choice is assumed to be independent of labor prices, output demand, and other input prices.

Typically, for a firm to purchase more energy-efficient equipment or structures, its initial capital outlay must be increased, i.e., while energy-inefficient durable goods have a lower initial asset acquisition price, *ceteris paribus*, they obviously also have larger operating costs. It is assumed that once the vintage $t-\tau$ investment is put in place, the energy per unit of capital ratio is fixed, i.e., for each vintage there are no _ex post_ energy-capital substitution possibilities. Hence, the present value optimizing firm will choose _ex ante_ the optimal energy efficiency of its new investment in equipment or structures on the basis of the expected time path of the price of energy relative to the price of equipment or structures. Under the assumption of myopic expectations (to be relaxed in future work), the optimal energy per unit of capital ratio at time $t-\tau$ is a decreasing function of the price of energy relative to the price of equipment or structures at time $t-\tau$. Given the above assumptions, once the investment is made at time $t-\tau$, this energy efficiency becomes embodied in the installed capital stock surviving into future time periods. This notion is now developed further.

Let δ be the constant annual rate of physical geometric deterioration for fixed capital equipment (δ_{EQ}) and non-residential structures (δ_{ST}). With geometric decay, a durable asset is never completely deteriorated. In order to truncate such an infinite life, it is assumed that scrappage occurs once 95% of the asset has physically deteriorated. Let T_i be the smallest integer at which such scrappage occurs, i.e., T_i is the physical lifetime of the asset in years.

Denote gross investment (in constant dollars) at time $t-\tau$ as $I_{t-\tau}$. The amount of vintage $t-\tau$ investment surviving to time t is denoted $K^i_{t,t-\tau}$ and is equal to the survival rate times investment, i.e.,

$$K^i_{t,t-t} = s^i_\tau I^i_{t-\tau} \qquad i = EQ, ST \tag{B1}$$

where the survival rate, under the asumption of geometric deterioration, is

$$s_\tau^i = \frac{1}{(1+\delta_i)^\tau} \tag{B2}$$

Under traditional capital accounting procedures (see, for example, Jorgenson-Griliches [1967] and Christensen-Jorgenson [1969]), the net capital stock at time t is computed as the sum over surviving vintages, i.e.

$$K_t^i = \sum_{\tau=0}^{T_i} K_{t,t-\tau}^i = \sum_{\tau=0}^{T_i} s_\tau^i I_{t-\tau}^i \quad , \qquad i = EQ,\ ST \tag{B3}$$

(Hereafter, for simplicity, we delete the i superscripts for EQ and ST.) Note that in this traditional framework, up to a factor of proportionality the investment goods of different vintages are assumed to be perfectly substitutable and thus summable. Specifically, the factor of proportionality between investment goods of vintage t and t-s in the capital stock at time t is simply $(1+\delta)^s$, and is thus a function only of differences in age and the rate of physical deterioration. The "quality" of two different vintages of investment is therefore dependent only on their age differences and δ, and in particular is independent of prices; Berndt [1983b, Section III] calls this the <u>price independent quality conversion ratio</u> between two durable goods.

A more general specification of quality ratios between investment goods of different vintages surviving to time t would allow the conversion ratio to depend on their embodied energy efficiency and the price of energy. Specifically, define this more general quality-adjusted amount of vintage $t-\tau$ investment surviving to time t as:

$$K_{t,t-\tau}^* = e_{t,t-\tau} s_\tau I_{t-\tau} = e_{t,t-\tau} K_{t,t-\tau} \tag{B4}$$

where, for the time being, $e_{t,t-\tau}$ is some function of relative energy prices embodied in the vintage t-τ investment good. Then compute the quality-adjusted aggregate capital stock at time t as the sum over quality-adjusted surviving vintages, i.e.,

$$K_t^* = \sum_{\tau=0}^{T} K_{t,t-\tau}^* = \sum_{\tau=0}^{T} e_{t,t-\tau} \, s_\tau \, I_{t-\tau} \tag{B5}$$

In the more general framework of (5), quality conversion ratios between investment goods of different vintages surviving to time t are not only a function of differences in age and the rate of deterioration as in (3), but also depend on differences in the energy efficiency factors $e_{t,t-\tau}$ which in turn depend on the history of relative energy prices. Berndt [1983, Section III] has called this an example of the <u>price dependent quality conersions ratio</u>. Note that if $e_{t,t-\tau} = 1$ for all t, then $K_t^* = K_t$, i.e., the traditional capital accounting procedure that assumes energy price-independent capital quality is a special case of energy price-dependent capital quality. Alternatively, according to (5), the various quality-adjusted investment goods of different vintages surviving to time t are assumed to be perfectly substitutable and thus summarable, but the quality-adjustment function $e_{t,t-\tau}$ is permitted to depend on the relative energy price embodied in the t-τ vintage investment. Moreover, if one uses (4) to rewrite (5) as

$$K_t^* = \sum_{\tau=0}^{T_i} e_{t,t-\tau} \, K_{t,t-\tau} \tag{B6}$$

then it is clear that quality-adjusted capital is a sum of multiplicative quality-adjusted surviving vintages.

Let us now divide both sides of (B6) by K_t, use (3), and then set the ratio of quality-adjusted to quality-unadjusted capital at time t equal to λ_t. This yields

$$\frac{K_t^*}{K_t} = \frac{\sum_{\tau=0}^{T} e_{t,t-\tau} K_{t,t-\tau}}{\sum_{\tau=0}^{T} K_{t,t-\tau}} = \lambda_t \tag{B7}$$

which implies that

$$K_t^* = \lambda_t K_t, \tag{B8}$$

where

$$\lambda_t = \frac{\sum_{\tau=0}^{T} e_{t,t-\tau} K_{t,t-\tau}}{\sum_{\tau=0}^{T} K_{t,t-\tau}} \tag{B9}$$

In logarithmic form, (B8) can be rewritten as

$$\ln K_t^* = \ln K_t + \ln \lambda_t \quad . \tag{B10}$$

Note that (10) is an hedonic quality adjustment equation of the form considered by Berndt [1983], where λ_t represents quality adjustment.

One possible representation for λ_t is the following. Earlier it was noted that if firms at time $t-\tau$ choose the optimal energy efficiency of their new capital investment at time $t-\tau$ on the basis of the price of energy relative to the new investment deflator for capital at time $t-\tau$, and if energy-capital substitution possibilities are zero once capital is installed, then one can write the weighted average of such energy prices embodied in the capital stock at time t as:

$$\hat{K}_t = \sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau} \qquad (B11)$$

where

$$p_{E,t-\tau} = \frac{P_{Energy,t-\tau}}{P_{Investment\ Deflator,\ t-\tau}} \qquad (B12)$$

Note that $\hat{K}_t$ obviously reflects the history of energy prices relative to new capital goods prices, and therefore can be expected to be inversely related to the energy efficiency embodied in the aggregate vintage-weighted capital stock.

Suppose that instead of changing over historical time, the relative price of energy at time $t-\tau$ had been constant at its t-time level, i.e., $p_{E,t-\tau} = p_{E,t}$, $\tau=0, \ldots, T$. Obviously, had this occurred, the firm choosing the optimal energy-efficiency for its plant and equipment would have chosen a different energy efficiency than was done historicaly when $p_{E,t-\tau} \neq p_{E,t}$. Under such an assumption, however, the weighted average of energy prices embodied in the capital stock (with constant relative energy prices) can be calculated as:

$$K'_t = \sum_{\tau=0}^{T} p_{E,t} K_{t,t-\tau} = p_{E,t} \sum_{\tau=0}^{T} K_{t,t-\tau} = p_{E,t} K_t \ . \qquad (B13)$$

Now, to compare the embodied energy efficiency of the capital stock at time t under constant relative energy prices with the embodied energy efficiency of the stock at time t given realized historical relative energy prices, the embodied energy inefficiency ratio (hereafter, EEIR) is defined as (B13) divided by (B11), i.e.

$$\text{EEIR}_t \equiv \frac{K'_t}{\hat{K}_t} = \frac{\sum_{\tau=0}^{T} p_{E,t} K_{t,t-\tau}}{\sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau}} = \frac{p_{E,t} K_t}{\sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau}} \tag{B14}$$

In interpreting (B14), it is useful to note that if relative energy capital prices were increasing over time, i.e., if $p_{E,t} > p_{E,t-\tau}$, $\tau=1, \ldots, T$, then $\text{EEIR}_t > 1$ -- that is to say, by current standards ($p_{E,t}$), the capital stock at time t would be energy-inefficient. Conversely, if relative energy prices were falling over time, by current standards the capital stock would be too energy-efficient, i.e., $\text{EEIR}_t < 1$. If, however, relative energy prices remained constant over at least T time periods, then the surviving capital stock at time t would, by current standards, have an $\text{EEIR}_t = 1$. It might also be noted that if there occurred over time autonomous improvements in energy efficiency unrelatd to the history of $p_{E,t}$ but related only to, say, Hicks-neutral technological progress, then this effect of technological change would appear both in (B11) and in (B13), and thus would cancel out in the ratio form (B14).

Suppose now one specified that the capital quality-adjustment relationshp as a function of relative energy prices takes the form

$$\lambda'_t = \text{EEIR}_t^{\,b_{KE}} \tag{B15}$$

which implies, using (B9), (B10), and (B14), that

$$\begin{aligned} \ln K^*_t &= \ln K_t + b_{KE} \ln \text{EEIR}_t \\ &= \ln K_t + b_{KE} \ln \left(\frac{p_{E,t} K_t}{\sum_{\tau=0}^{T} p_{E,t-\tau} K_{t,t-\tau}} \right) \end{aligned} \tag{B16}$$

It is expected that $b_{KE} < 0$, i.e., increases in the embodied energy inefficiency of the capital stock reduces its quality, ceteris paribus.

We now examine how (B16) relates to the energy-efficiency multiplicative vintage weighting scheme of (B7) where

$$\frac{K_t^*}{K_t} = \frac{\sum_{\tau=0}^{T} e_{t,t-\tau} K_{t,t-\tau}}{\sum_{\tau=0}^{T} K_{t,t-\tau}} = \lambda_t \tag{B7'}$$

To do this, we set λ_t of (B7) equal to λ'_t of (B15), and obtain

$$\sum_{\tau=0}^{T} e_{t,t-\tau} \left(\frac{K_{t,t-\tau}}{K_t}\right) = \sum_{\tau=0}^{T} \left[\left(\frac{p_{E,t-\tau}}{p_{E,t}}\right)\left(\frac{K_{t,t-\tau}}{K_t}\right)\right]^{-b_{KE}} \tag{B17}$$

Hence, in general, it appears that one cannot solve analytically for the $e_{t,t-\tau}$ vintage weights as a function of the relative energy prices and b_{KE} consistent with the quality-adjustment specification (B16).

Two special cases, however, are of interest. First, if $b_{KE} = 0$, then from (B17) and (B3) it is clear that

$$e_{t,t-\tau} = 1 \text{ for all } t,\tau. \tag{B18}$$

This is not surprising, for if $b_{KE} = 0$ in (B16), it implies that $\ln K^*_t = \ln K_t$, i.e., quality-adjusted and traditional measures of capital coincide, and embodied energy inefficiency is irrelevant. This case is, of course, the traditional capital measurement procedure. Second, however, if $b_{KE} = -1$, then from (B17), it is clear that

$$e_{t,t-\tau} = \frac{p_{E,t-\tau}}{p_{E,t}} \qquad \text{(B19)}$$

i.e., when $b_{KE} = -1$ the capital quality adjustment specification (16) can be interpreted as weighting each surviving vintage $t-\tau$ investment at time t by the historical real energy price at time $t-\tau$ (embodied in that vintage of capital) relative to the current real energy price embodied in current investment. If, for example, real energy prices at time t were twice as large as at time $t-\tau$ when $b_{KE} = -1$ the $t-\tau$ investment would be quality-adjusted by multiplying $K_{t,t-\tau}/K_t$ by 1/2, i.e., the quality-adjustment would revalue downward by 50% the traditionally measured $t-\tau$ capital surviving to time t.

In summary, when $b_{KE} = 0$, multiplicative quality adjustment on surviving $t-\tau$ vintages at time t is simply unity, while when $b_{KE} = -1$, multiplicative quality adjustment on surviving $t-\tau$ vintages at time t is inversely proportional to the ratio of relative energy prices at times t and $t-\tau$.

The previous discussion suggests that an alternative vintage weighting scheme for (B9) might be the following:

$$\tilde{\lambda}_t = \sum_{\tau=0}^{T} \left(\frac{p_{E,t-\tau}}{p_{E,t}}\right)^{-\alpha} \left(\frac{K_{t,t-\tau}}{K_t}\right) \qquad \text{(B20)}$$

where α could possibly be interpreted as some function of the ex ante substitution elasticity between energy and capital. Note that when $\alpha = 0$ and $\alpha = -1$, the resulting multiplicative vintage quality-adjustment weights correspond exactly to the weights implied when $b_{KE} = 0$ and $b_{KE} = -1$, respectively. An empirical disadvantage of (20), however, is that it cannot be calculated unless α were known, whereas the calculation of $EEIR_t$ in (14) can proceed independently of knowledge of b_{KE}. While in principle α could be estimated econometrically along with other parameters, each time series observation on $\hat{\lambda}_t$ would be a lengthy expression containing all surviving vintages of capital, each such vintage being multiplied by a nonlinear function of α. By contrast, the specification of quality adjustment for $EEIR_t$ (B14) and λ' (B15) is computationally much more convenient, and therefore is calculated here.

This concludes our discussion on theoretical considerations involved in the development of a measure of capital vintage-specific quality adjustment. We now turn to consideration of data sources and procedures necessary to construct our proposed $EEIR_t$ index.

DATA SOURCES FOR EEIRτ CONSTRUCTION

In order to implement the construction of an EEIR data series for U.S. manufacturing, 1947-77, it is necessary to assume constant geometric deterioration rates δ_{EQ} and δ_{ST}, calculate the implied physical lifetimes T_{EQ} and T_{ST} and measures of vintage $t-\tau$ investment surviving to time t ($K^{EQ}_{t,t-\tau}$ and $K^{ST}_{t,t-\tau}$), develop traditional measures of the capital stock K^{EQ}_t and K^{ST}_t as the sum over surviving vintages, and then use data on the history of relative energy prices $p^{EQ}_{E,t-\tau}$ and $p^{ST}_{E,t-\tau}$ and equation (B14) to calculate $EEIR_t$ ratios for EQ and ST.

Estimates of δ_{EQ} and δ_{ST} are taken from Berndt [1972] (also used in, among other studies, Berndt-Wood [1975, 1979]) and turn out to be 0.135

and 0.071, respectively. Briefly, these figures are obtained as the annual average geometric rates of physical deterioration implicit in the net aggregate capital stock estimates calculated by the U.S. Department of Commerce, Office of Business Economics (see Wasson, Musgrave and Harkins [1970], and Grose, Rottenberg and Wasson [1969], and the data appendix of Berndt [1982]), which in turn are based on the fixed Winfrey mortality distribution applied to past data on gross investment for a number of different types of producers' durable equipment and nonresidential structures, each with assumed straight line depreciation.

Given these estimates of δ_{EQ} and δ_{ST}, the implied physical lifetimes (defined as the smallest age in integers at which 95% of the asset is physically deteriorated) are 21 years for EQ and 41 years for ST. We therefore set $T^{EQ} = 21$ and $T^{ST} = 41$.

Investment data for equipment and structures in U.S. manufacturing since the late 1800s, in current and constant dollars to 1979, have graciously been made available to us by Mr. J. Silverstein of the Bureau of Economic Analysis at the U.S. Department of Commerce. Note that since our principal data set begins in 1947 and since $T^{ST} = 41$ years, it is necessary to obtain data back to at least 1906. Investment deflators for equipment (P_{EQUIP}) and structures (P_{STRUC}) are computed as the ratio of current to constant dollar investment, and are normalized to unity in 1972. These deflators are presented in Table 1 (1906-1947) and Table 2 (1947-1977). The corresponding data on the energy price index (PE) over the 1906-47 time period have been developed by Berndt-Wood [1983]; the P_E series 1947-71 are from Berndt-Wood [1975], and have been spliced with the Norsworthy-Harper [1981] data series to

TABLE 1

PRICE INDEXES FOR ENERGY, NEW EQUIPMENT, AND NEW STRUCTURES IN U.S. MANUFACTURING, 1906-1947

YEAR	PE	PEQUIP	PSTRUC	PE/PEQUIP	PE/PSTRUC
1906	.3539	.1285	.1170	2.754	3.024
1907	.3646	.1390	.1170	2.624	3.115
1908	.3587	.1299	.1135	2.761	3.161
1909	.3446	.1464	.1142	2.354	3.017
1910	.3552	.1470	.1170	2.416	3.036
1911	.3544	.1632	.1170	2.172	3.028
1912	.3702	.1561	.1220	2.372	3.034
1913	.3814	.1532	.1348	2.498	2.831
1914	.3754	.1633	.1199	2.298	3.131
1915	.3519	.1803	.1220	1.952	2.884
1916	.3902	.1968	.1461	1.983	2.671
1917	.5533	.2444	.1752	2.264	3.159
1918	.6231	.3163	.2000	1.970	3.116
1919	.6202	.3257	.2340	1.904	2.650
1920	.8394	.3356	.3022	2.501	2.778
1921	.6705	.3118	.2192	2.150	3.059
1922	.6926	.2719	.2105	2.547	3.290
1923	.6175	.2856	.2384	2.162	2.590
1924	.5589	.2887	.2340	1.936	2.389
1925	.5511	.2904	.2340	1.898	2.355
1926	.5676	.2891	.2341	1.963	2.425
1927	.5218	.2892	.2290	1.804	2.278
1928	.4975	.2911	.2291	1.709	2.171
1929	.4893	.3082	.2241	1.588	2.183
1930	.4808	.2916	.2107	1.649	2.282
1931	.4449	.2673	.1830	1.664	2.431
1932	.4471	.2429	.1546	1.841	2.892
1933	.4103	.2314	.1489	1.773	2.755
1934	.4514	.2728	.1703	1.654	2.651
1935	.4410	.2762	.1703	1.597	2.589
1936	.4296	.2763	.1816	1.555	2.365
1937	.4358	.2969	.2071	1.468	2.105
1938	.4419	.3095	.2037	1.428	2.169
1939	.4147	.3091	.2014	1.341	2.059
1940	.4078	.3259	.2099	1.251	1.942
1941	.4210	.3498	.2319	1.204	1.816
1942	.4214	.3599	.2638	1.171	1.597
1943	.4335	.3589	.2966	1.208	1.461
1944	.4452	.3592	.2840	1.239	1.568
1945	.4579	.3572	.2863	1.282	1.600
1946	.4983	.3886	.3107	1.282	1.603
1947	.5589	.4071	.3803	1.373	1.470

TABLE 2

PRICE INDEXES FOR ENERGY, NEW EQUIPMENT, AND NEW STRUCTURES IN U.S. MANUFACTURING, 1947-1977

YEAR	PE	PEQUIP	PSTRUC	PE/PEQUIP	PE/PESTRUC
1947	.5589	.4071	.3803	1.373	1.470
1948	.7280	.4591	.4261	1.586	1.709
1949	.6688	.4921	.4265	1.359	1.568
1950	.6788	.5070	.4298	1.339	1.579
1951	.6996	.5511	.5271	1.269	1.327
1952	.7150	.5586	.5473	1.280	1.306
1953	.7126	.5708	.5493	1.249	1.297
1954	.7286	.5783	.5329	1.260	1.367
1955	.7505	.6103	.5455	1.230	1.376
1956	.7666	.6576	.5860	1.166	1.308
1957	.7714	.7024	.6116	1.098	1.261
1958	.7788	.7216	.5959	1.079	1.307
1959	.7643	.7436	.5772	1.028	1.324
1960	.7714	.7561	.5680	1.020	1.358
1961	.7692	.7599	.5591	1.012	1.376
1962	.7696	.7695	.5603	1.000	1.373
1963	.7531	.7712	.5847	.976	1.288
1964	.7767	.7807	.6115	.995	1.270
1965	.7748	.7951	.6300	.975	1.230
1966	.7830	.8204	.6609	.954	1.185
1967	.7780	.8505	.6941	.915	1.121
1968	.8014	.8727	.7167	.918	1.118
1969	.8187	.9025	.8016	.907	1.021
1970	.8155	.9442	.8783	.864	.928
1971	.9205	.9812	.9534	.938	1.065
1972	1.0000	1.0000	1.0000	1.000	1.000
1973	1.1254	1.0272	1.0973	1.096	1.026
1974	1.5484	1.1235	1.1938	1.378	1.297
1975	1.9586	1.3102	1.4080	1.495	1.391
1976	2.1627	1.4017	1.3860	1.543	1.560
1977	2.5171	1.4801	1.4664	1.701	1.717

extend the series to 1977. These P_E data, normalized to unity in 1972, are presented in Table 1 (1906-47) and Table 2 (1947-77). Plans are currently underway to update the P_E series to 1980.

Given these time series on P_E, P_{EQUIP}, and P_{STRUC}, we calculate relative energy-capital prices as the ratios P_E/P_{EQUIP} and P_E/P_{STRUC}; these relative energy prices are listed in Table 1 (1906-47) and Table 2 (1947-77).

In order to compute EEIR measures for EQ and ST, 1947-77, we first calculate survival rates by age (see (B2)) and multiply the survival rate for each τ at time t by the amount of investment that occurred at time $t-\tau$, separately for EQ and ST, thereby obtaining annual data on $K^{EQ}_{t,t-\tau}$ and $K^{ST}_{t,t-\tau}$. Using (B14), we then weight these vintages of capital surviving to time t by the relative energy-capital price existing when the $t-\tau$ vintage was new, i.e., by $P_{E,t-\tau}$. This yields an annual time series of EEIR measures for equipment and structures, 1947-77, which are presented in Table 3 below. Note that these EEIR ratios reflect the current price of energy to that energy price embodied in the equipment and structure stocks. For equipment, this ratio reaches a minimum in 1959, while for structures the minimum point occurs in 1961; both ratios reach sample maximum values in 1977.

TABLE 3

EEIR VALUES FOR EQUIPMENT AND STRUCTURES

U.S. MANUFACTURING, 1947-77

YEAR	EEIR$_{EQ}$	EEIR$_{ST}$
1947	1.041	0.728
1948	1.132	0.868
1949	0.976	0.819
1950	0.969	0.840
1951	0.933	0.724
1952	0.964	0.733
1953	0.945	0.747
1954	0.964	0.804
1955	0.949	0.825
1956	0.916	0.802
1957	0.887	0.793
1958	0.894	0.838
1959	0.869	0.863
1960	0.879	0.894
1961	0.891	0.914
1962	0.899	0.921
1963	0.901	0.876
1964	0.941	0.877
1965	0.931	0.862
1966	0.926	0.846
1967	0.911	0.820
1968	0.935	0.837
1969	0.939	0.784
1970	0.916	0.735
1971	1.000	0.782
1972	1.057	0.824
1973	1.134	0.856
1974	1.327	1.078
1975	1.332	1.142
1976	1.305	1.257
1977	1.337	1.350

AGGREGATION OF $EEIR^{EQ}$ AND $EEIR^{ST}$

In order to aggregate the $EEIR^{EQ}$ and $EEIR^{ST}$ indices, it is, of course, desirable to employ weights that reflect the relative importance of energy consumption by equipment (primarily motive power and process heat use) and structures (space heating and lighting). Although it is clear that motive power and process heat uses dominate in energy consumption and therefore that the equipment EEIR should be weighted more heavily than that for structures, unfortunately very little data is available on the functional end-use of electricity, and thus choice of weights is not clear.

DuBoff [1979] has used census and Federal Power Commission data to calculate estimates of total electricity (not total energy) consumption by functional end-use; for the years 1939 and 1954, DuBoff [1979, Table 23, p. 87] estimates the percent of electricity used for lighting, was 11% and 10%, for power 67% and 62%, and for process heat 22% and 28%, respectively. DuBoff [1979, Appendix D, pp. 215-217] cites an unpublished study by Strout [1961] who estimates these 1939 and 1954 electricity functional end-uses as lighting--14% and 12%; power--62% and 58%; and process heat--24% and 30%, respectively. The functional end-uses of electricity in manufacturing are also discussed briefly by Foss [1963, pp. 13-14]. Unfortunately, we are not aware of any studies on the functional end-use of total energy in U.S. manufacturing.

It is plausible to argue, however, that at least 75% and perhaps as much as 90% of all energy use in the U.S. manufacturing sector is relatoed to the operation of equipment for purposes such as motors, power, and process heating, while somewhere between 10 and at most 25% of energy use is related to the operation of structures, primarily for space heating and lighting.

Given these percentages, we have calculated four alternative total EEIR indexes:

$$\text{EEIR } 10\text{-}90 = .10 * \text{EEIR}^{ST} + .90 * \text{EEIR}^{EQ}$$
$$\text{EEIR } 15\text{-}85 = .15 * \text{EEIR}^{ST} + .85 * \text{EEIR}^{EQ}$$
$$\text{EEIR } 20\text{-}80 = .20 * \text{EEIR}^{ST} + .80 * \text{EEIR}^{EQ}$$
$$\text{EEIR } 25\text{-}75 = .25 * \text{EEIR}^{ST} + .75 * \text{EEIR}^{EQ}$$

These four series are listed in Table 4 below.

One clear finding apparent from Table 4 is that the four alternative aggregate EEIR indices are very similar to one another; their 1947 values vary between 0.911 and 0.981, while their 1977 values fall in the even narrower interval of 1.337 to 1.339. Each hits a maximum value in 1977, and minimum values either in 1959 (EEIR 10-90 or 15-85) or in 1957 (EEIR 20-80 or 25-75). While we have a slight prior preference for the 15-85 or 10-90 series (since it seems plausible to us that the structures use of energy is rather small), it is comforting that the aggregate EEIR measures are rather insensitive to choice between the four alternative weighting schemes.

TABLE 4

EMBODIED ENERGY INEFFICIENCY RATIO (EEIR)
AND AVERAGE AGE OF FIXED CAPITAL STOCK
IN U.S. MANUFACTURING, 1947-1977

YEAR	EEIR 10-90	EEIR 15-85	EEIR 20-80	EEIR 25-75	AVERAGE AGE
1947	.981	.956	.932	.911	8.278
1948	1.090	1.070	1.053	1.036	7.089
1949	.952	.941	.931	.921	6.669
1950	.950	.941	.932	.925	6.725
1951	.903	.889	.876	.863	6.808
1952	.924	.910	.896	.883	6.659
1953	.920	.908	.896	.884	6.591
1954	.944	.935	.925	.916	6.567
1955	.935	.927	.920	.913	6.545
1956	.902	.896	.890	.883	6.587
1957	.877	.871	.866	.861	6.463
1958	.888	.885	.882	.879	6.404
1959	.868	.868	.867	.867	6.615
1960	.881	.882	.883	.884	6.841
1961	.894	.895	.896	.898	6.968
1962	.902	.903	.904	.906	7.103
1963	.898	.896	.895	.893	7.155
1964	.933	.929	.926	.922	7.152
1965	.923	.919	.915	.911	7.033
1966	.917	.913	.908	.904	6.741
1967	.901	.896	.892	.887	6.377
1968	.925	.920	.915	.909	6.135
1969	.924	.916	.908	.900	6.041
1970	.898	.889	.880	.871	5.954
1971	.978	.968	.957	.946	5.974
1972	1.035	1.024	1.013	1.002	6.101
1973	1.109	1.097	1.084	1.071	6.161
1974	1.307	1.297	1.287	1.276	6.071
1975	1.318	1.311	1.303	1.296	6.977
1976	1.302	1.300	1.298	1.296	6.127
1977	1.337	1.338	1.338	1.339	6.049

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