

**Energy Use, Technical Progress and Productivity
Growth: A Survey of Economic Issues**

by

Ernst R. Berndt

MIT-CEPR 90-006WP

March 1990

M.I.T. LIBRARIES
MAR 14 1991
RECEIVED

ENERGY USE, TECHNICAL PROGRESS AND PRODUCTIVITY GROWTH:

A SURVEY OF ECONOMIC ISSUES

by

Ernst R. Berndt*
Professor of Applied Economics
Massachusetts Institute of Technology
Alfred P. Sloan School of Management
50 Memorial Drive, E52-452
Cambridge, MA. 02139 U.S.A.

The helpful comments of Thomas G. Cowing, Sam H. Schurr, David O. Wood and two anonymous referees are gratefully acknowledged, as is financial support from the MIT Center for Energy Policy Research.

Revision Dated February 5, 1990

ABSTRACT

This is a survey paper for non-specialists on interactions between energy and productivity growth. The first half of the paper surveys the general economic literature linking technical progress to realized gains in productivity growth. The second half of the survey focuses in particular on the important role of energy in linking technical progress to productivity growth, and contains an overview of a great deal of literature, both classic and recent.

I. INTRODUCTION

The relationships among technical progress, productivity growth and energy use are not only extremely important, but they are also exceedingly complex. It is not surprising, therefore, that these interactions can be viewed insightfully from a number of differing vantages. In this paper I survey the existing literature, as viewed by an economist.

The outline I follow is as follows: The first half of the paper surveys the general economic literature linking technical progress to realized gains in productivity growth. The second half of the survey focuses in particular on the important role of energy in linking technical progress to productivity growth. More specifically, in Section II I consider the economic literature relating technical progress to various types of productivity growth, summarize the economic framework of cost and production, and distinguish embodied and disembodied technical progress. This section also contains a very brief overview on principal empirical findings to date. Then in Section III I narrow my focus and examine how energy consumption patterns simultaneously effect and are effected by technical progress and productivity growth. This section contains an overview of a great deal of literature, both classic and recent. Finally, in Section IV I present concluding remarks and observations.

Since this survey focuses on energy issues, I will of course overview the existing literature on the relationship between energy price shocks and the 1973-74 productivity growth slowdown. A number of interesting explanations for this slowdown have been offered that are essentially unrelated to energy issues (e.g., US government monetary and fiscal policy in 1973-75 allegedly was not accommodating), but due to space constraints, I will not discuss them here.¹

II. RELATIONSHIPS AMONG TECHNICAL PROGRESS AND PRODUCTIVITY GROWTH:

AN ECONOMIC FRAMEWORK

Ever since the pioneering research of Jan Tinbergen [1942] and Robert M. Solow [1957], the relationships among technical progress and productivity growth

have been envisaged within the economic theory of cost and production. In the next few paragraphs, therefore, I present and summarize these theoretical foundations.

II.A. Cost and Production Functions

Define a set of engineering relationships among inputs and output as the production function, which indicates the maximum possible flow of output attainable (denoted Y), given alternative quantity flows of the n inputs (denoted X_1, X_2, \dots, X_n) and the state of technical knowledge (denoted A). Write this production function in implicit form as

$$Y = f(X_1, X_2, \dots, X_n; A). \quad (1)$$

A useful way of viewing the production function relationship is to think of it as a book whose pages contain alternative blueprint designs for combining inputs to produce the output level Y . Obviously, the production function and the book of blueprints must be consistent with laws of nature and other engineering relationships. While laws of nature are by definition stable and do not change over time, our understanding and discovery of these laws, as well as our ability to exploit technological possibilities, has improved with time. One way of accounting for such advances in the state of technical knowledge, therefore, is to think of them as adding new pages to the book of blueprints. For this reason, the variable A is included in the production function (1).

It is often convenient to structure the relationships among technical progress and productivity growth in terms of the dual cost function. A cost function indicates the minimum possible total cost C of producing a given level of output, given prices of the n inputs (denoted P_1, P_2, \dots, P_n) and the state of technical knowledge A . Write the cost function as

$$C = g(P_1, P_2, \dots, P_n; Y; A). \quad (2)$$

Obviously, the form of the dual cost function g in (2) must reflect the parameters of technology embodied in the production function f of (1).

Moreover, it is important to note that advances in technical knowledge that shift outward the production function, shift downward the dual cost function.

II.B. Factor-Specific and Multifactor Productivity Growth

Early in this century when agriculture played a much larger role in the economy than it does in industrialized economies today, analysts typically identified the word productivity with average yield per acre, i.e. Y/X_1 , where Y was yield per year and X_1 was the number of acres. This focus in agricultural economics on yield per acre is but one example of factor-specific productivity.

Another example of factor-specific productivity, namely, average labor productivity, is more common today than is yield per acre. Average labor productivity is defined as Y/L -- output divided by labor input -- where labor input is typically measured as hours at work. On average since World War II, in both the European and North American economies, average labor productivity in the manufacturing sector has grown about 2% per year; in Japan the growth rate in labor productivity over the last two decades has averaged at 5% per year. Increases in average labor productivity are typically interpreted as being due to increases in capital per hour at work (capital deepening), scale economies, and/or advances in the state of technical knowledge (such as, perhaps, learning which occurs after labor intensive tasks are performed repetitively).

A final example of factor-specific productivity of special relevance here, commonly known as average energy productivity, is defined as output divided by energy input, where the latter can be measured in a number of ways (such as, for example, ton-equivalents of coal or British thermal units). From the end of World War II until the early 1970's, in many economies average energy

productivity grew at about 1/2% per year, reflecting in part advances in the state of knowledge. After OPEC-I (1973-74) and especially following OPEC-II (1979-80), average energy productivity increased more rapidly, due in large part to the replacement of energy-inefficient capital equipment with more energy-efficient designs.

These are but three examples of factor-specific productivity growth measures. One could, of course, think of other inputs and then compute their average productivity growth rates. Rather than doing that, however, I believe it is more useful to consider the determinants affecting growth rates of factor-specific productivities. Begin by simply dividing both sides of the production function (1) by X_i , thereby obtaining

$$Y/X_i = f(X_1, X_2, \dots, X_n; A)/X_i, \quad (3)$$

which indicates that growth in factor-specific productivity for the i^{th} input generally depends on the levels of all n inputs, as well as advances in the state of technical knowledge. Alternatively, as long as firms minimize costs, one can employ the cost function notion and obtain optimal (cost-minimizing) input-output coefficients for each of the n inputs into production, invert them and obtain factor-specific productivity measures as

$$Y/X_i = h(P_1, P_2, \dots, P_n; Y; A). \quad (4)$$

Equation (4) highlights the fact that factor-specific productivity measures are dependent on, inter alia, the prices of the n inputs. This dependence is closely related to the notion of price elasticity of demand. In particular, consider the following experiment: Suppose the price of the j^{th} input changes, all other input prices remain fixed, while the state of technology A and the level of output Y also remain fixed. By how much does the optimal (cost-minimizing) demand for the i^{th} input change?

This price responsiveness of demand for input i is called the price elasticity of demand, and is typically formulated in logarithmic terms as

$$\epsilon_{ij} \equiv \frac{\partial \ln X_i}{\partial \ln P_j} \Big|_{Y=\bar{Y}, A=\bar{A}, P_k = \bar{P}_k (k \neq j)} \quad (5)$$

Now define the average productivity elasticity η_{ij} as the response in the average productivity of the i^{th} input due to a change in the price of the j^{th} input, where all other input prices, the state of technology and the level of output are fixed, i.e.

$$\eta_{ij} \equiv \frac{\partial \ln (Y/X_i)}{\partial \ln P_j} \Big|_{Y=\bar{Y}, A=\bar{A}, P_k = \bar{P}_k (k \neq j)} \quad (6)$$

One can easily show that the average productivity elasticity η_{ij} is simply the negative of the price elasticity ϵ_{ij} , i.e. $\eta_{ij} = -\epsilon_{ij}$.

Consider, for example, the fact that a number of econometric studies have shown that in many manufacturing processes, energy and labor are substitutable inputs. As the price of labor increases, ceteris paribus, firms substitute away from labor and towards energy; this implies that the price elasticity $\epsilon_{EL} > 0$ (where E is energy and L is labor). This energy-labor substitutability also implies that the average energy productivity elasticity with respect to labor is negative, i.e. $\eta_{EL} < 0$; increases in the price of labor, ceteris paribus, induce substitution away from labor (increasing Y/L) and towards energy (thereby decreasing the average energy productivity Y/E).

While factor-specific average productivity measures contain useful summary information, they are subject to one very serious objection. Namely, it is not at all clear that increases in factor-specific average productivity are always desirable.² Consider, for example, average labor productivity. As capital

machines initially substituted for labor, Y/L increased. This capital-labor substitution could conceivably continue virtually forever, until finally a given level of output could be produced with but one unit of labor and an incredibly complex and expensive network of robots, computers and machines. While this extremely high level of Y/L might be possible in an engineering sense, it could also be very expensive -- the combined capital and labor costs in such a low labor, high capital-intensive setting could be much higher than if more labor and less capital were employed. Similarly, one might in fact be able to build "super machines" that were incredibly energy efficient (near the limits implied by the laws of thermodynamics), but the combined energy and capital costs of operating such energy efficient machines might be considerably larger than if less energy-efficient designs were employed instead.

These two examples highlight the important economic fact that firms, households and societies are not necessarily better off simply because the factor-specific productivity of some input has increased; the consumption of other inputs may have increased as a result, and thus the total resource costs to society might be larger, the same as, or less than before. What is needed is a measure of productivity growth that recognizes the fact that all inputs are scarce, and that the desired productivity growth is that growth which results from the combined savings over all inputs, not just one input.

This consideration has led to the notion of multifactor productivity (MFP) growth, defined as growth in output minus growth in aggregate input, i.e.

$$\text{MFP} \equiv \dot{A}/A = \dot{Y}/Y - \dot{X}/X, \quad (7)$$

where growth in aggregate input is a weighted sum of growth in the individual inputs, i.e.

$$\dot{X}/X \equiv \sum_{i=1}^n w_i (\dot{X}_i/X_i) \quad (8)$$

with the w_i weights being cost shares of the i^{th} input in total costs of production.

Unlike factor-specific productivity measures, increases in MFP growth are always desirable, for they indicate that more output is being obtained from a given bundle of inputs. Due in large part to this clearer interpretation, major national statistical agencies, such as the U.S. Bureau of Labor Statistics, are now calculating and publishing measures of MFP growth on a regular basis.

While MFP growth measures are therefore in theory clearly preferable to factor-specific productivity growth measures, in practice the measurement of MFP growth requires more data than factor-specific productivity -- price and quantity measures of all inputs are necessary. In this context, it is important to recognize that the calculated MFP residual in (8) may in fact reflect not only the effects of advances in the state of knowledge, but also a host of measurement errors.

II.C. Embodied and Disembodied Technical Progress

In the previous paragraphs I have presented alternative measures of productivity growth, and have argued that for most purposes the MFP growth measure is preferable to single-factor measures. This raises the next important issue: How are various types of advances in knowledge related to MFP growth?

Over the last few decades an extensive literature has developed in economics and economic history concerning the classification of technical progress. One important distinction frequently made is that between embodied and disembodied technical progress.³

Embodied technical progress refers to engineering design and performance advances that can only be embodied in new plant or equipment; older equipment cannot be made to function as economically as the new, unless a costly remodeling or retrofitting of equipment occurs. To the extent that technical progress is embodied, its effects on costs and production depend critically on the rate of diffusion of the new equipment, which in turn depends on investment and the resulting vintage composition of the surviving capital stock.

By contrast, disembodied technical progress refers to advances in knowledge that make more effective use of all inputs, including capital of each surviving vintage (not just the most recent vintage). In its pure form, disembodied technical progress proceeds independently of the vintage structure of the capital stock. The most common example of disembodied technical progress is perhaps the notion of learning curves, in which it has been found that for a wide variety of production processes and products, as cumulative experience and production increase, learning occurs which results in ever decreasing unit costs. Some have called this type of learning process "learning by doing," "learning through the examples of others," or "learning by using." Classic examples include the production of aircraft frames and ships during World War II.⁴

While the distinction between embodied and disembodied technical progress is in principle quite clear, in practice and in history one frequently finds that these two types of technical progress interact with one another in a complex and dynamic manner. This will be discussed further in Section III.A.

II.D. A Brief Summary of the Principal Recent Empirical Findings on Multifactor Productivity Growth

A great deal of literature has appeared in the last twenty years concerning abrupt changes in multifactor (MFP), labor and energy productivity

growth since 1970. Detailed reviews and critiques of this literature can be found in, among others, Martin N. Baily [1981], Ernst R. Berndt and David O. Wood [1986a,b], Edward F. Denison [1985], John W. Kendrick [1983], Assar Lindbeck [1983], J. Randolph Norsworthy, Michael Harper and Kent Kunze [1979], and Mancur Olson [1988].

The first important common finding of this literature is that in virtually all countries, MFP and labor productivity growth rates declined sharply following the 1973-74 and 1979-80 OPEC oil price shocks. This temporal coincidence between productivity growth breaks and energy price shocks has naturally focused much attention on the relationship between unexpected energy price changes and productivity growth.⁵

A second important finding is that in the manufacturing sectors of Canada and especially the U.S., MFP growth began falling much earlier than 1973-74 -- as far back as 1965. For Japan, however, the sharp break in MFP occurred only after 1973-74. Moreover, MFP growth increased following investment spurts -- in the U.S., after 1977-80, and in Japan, after 1965 and before 1977.

A third significant set of findings is that measures of MFP growth depend critically on how one adjusts the inputs for quality change, and how one also adjusts for short-run cyclical changes in capacity utilization. Either of these adjustments can be decisive.

A fourth key finding in the empirical literature to date is that gains in energy conservation -- increases in average energy productivity -- typically followed the energy price shocks with a considerable time lag, and accelerated only after substantial investment occurred. This result simply reflects the fact that major changes in energy use patterns can occur only as the capital stock is replaced with more energy-efficient capital.

Fifth, data from the US Bureau of Labor Statistics show a resurgence in the growth rates of labor and multifactor productivity beginning in 1983, particularly in the manufacturing sector.⁶ Note that in about 1983 in the US, real energy prices again began to fall.

Sixth and finally, the time patterns of labor, energy and multifactor productivity growth have differed considerably over the last twenty years, both within and among the various sectors of the OECD economies. An important implication of this, therefore, is that one must be careful and precise before talking about "the" productivity growth slowdown.

Having presented the economic framework in which technical progress and various types of productivity growth can be considered, and having very briefly reviewed the principal empirical evidence to date, I now focus on energy consumption and turn to an examination of interactions among energy use, technical progress and productivity growth.

III. ENERGY USE, TECHNICAL PROGRESS AND PRODUCTIVITY GROWTH

In this section I focus on the important role of energy use in interacting with technical progress and productivity growth. I will attempt to demonstrate the insights one can obtain from the economic framework reviewed in the previous pages. Four examples will be given, each of which in one way or another illustrates the importance of embodied and disembodied technical progress.

III.A. THE SCHURR HYPOTHESIS: AN EXAMPLE OF INTERACTIONS BETWEEN EMBODIED AND DISEMBODIED TECHNICAL PROGRESS

In a series of studies beginning in the early 1950's, Sam Schurr and his associates have hypothesized that the electrification of US industry in the early twentieth century contributed significantly both to labor and MFP growth.⁷

This hypothesis is of special interest to productivity analysts, for it implies that even if labor and electricity were substitutable inputs in production (recall the discussion in Section II.B above), increases in electrification still resulted in both enhanced labor and MFP growth, i.e. the technical progress effects dominated the substitution effects.

The Schurr hypothesis in fact incorporates several hypotheses concerning the distinct and interactive contributions of electrification to productivity growth via embodied and disembodied technical progress. In essence it portrays the interaction between one type of energy having a special flexible form -- electricity -- and the introduction and adoption of new capital equipment and machinery driven by this new energy form.

More specifically, at the turn of the century electricity and the fluid fuels came into increasing use, due in large part to their relative abundance, their low prices, and their flexibility property relative to the solid fuels that had previously dominated energy supply. In the case of electricity, technical progress was embodied in the sense that low-cost electricity was now available from more efficient steam generation, and no longer required access to water wheels and running water.

In turn, these characteristics of electricity -- low cost, abundance and enhanced flexibility in use -- provided the seeds for the discovery, development and use of new product innovations. According to the historical literature, these advances in technical knowledge eventually led to the design and introduction of new "group drive" and ultimately "unit drive" machinery and equipment, thereby rationalizing the factory floor and inducing additional process innovations. In particular, the factory floors could now be laid out in a more logical, natural manner, using perhaps the new scientific management principles

of Frederick Taylor, rather than being physically constrained by systems of belts and shafts. This demonstrates the interactive and dynamic nature of embodied and disembodied technical progress, and between product and process innovations.

One other feature of the Schurr hypothesis that has not received much attention is the important role of market structure in facilitating the diffusion of technical progress. In particular, electricity generating companies early on discovered the importance of scale economies, and this created possibilities for natural monopoly. Had natural monopolies been permitted to operate without any interference, the prices charged by the monopolies could have exceeded production costs and thereby could have slowed down the diffusion process considerably. What actually happened, of course, is that rather early in their history these electricity generating companies were regulated, prices were set so that economic profits were approximately zero, and promotional pricing strategies and policies were adopted that resulted in low electricity prices and rapid diffusion.

As a final comment, it is worth noting that the Schurr hypothesis has been implemented and assessed using econometric methods. In particular, based on pooled cross-section and time series data by state from the 1909, 1914 and 1919 censuses in the U.S., Berndt and Wood [1984b] have quantified the effects of electrification in the total manufacturing and cotton goods industries. Among their findings is the result that already in the 1909-1919 time period, prior to the very rapid increase in electrification, variations among states in overall horsepower and, more importantly, their electrified horsepower per unit of capital, had important and positive labor productivity effects, over and above the additional costs incurred by the manufacturing and cotton goods firms in

purchasing such equipment. Related econometric findings on the Schurr hypothesis have also been reported by Woolf [1980,1983,1984] and Berndt [1986].

III.B. THE BIASED TECHNICAL CHANGE HYPOTHESIS: DISEMBODIED TECHNICAL PROGRESS

A rather different body of literature indicating a special role for both electric and non-electric energy inputs in the productivity growth process has appeared in the last decade, and is typically referred to as the biased technical change hypothesis. Its principal spokesman has been Dale W. Jorgenson.⁸

Using the theory of cost and production, Jorgenson specifies a production model that employs historical data for 35 industries in the U.S.. He then estimates parameters in systems of input demand equations for capital, labor, energy, and non-energy intermediate materials. The right-hand or "explanatory" variables in these statistical demand equations are prices of the inputs and time (the latter, 1 in 1958, the first year of the sample, 2 in 1959, etc.). This time variable represents an attempt to capture the effects of disembodied technical progress, which implicitly is assumed to increase lockstep with the passage of time. Within this framework, no attempt is made to account explicitly for embodied technical change.⁹

Based on annual US data since 1958, Jorgenson obtains the striking finding that in almost every one of the 35 sectors examined, the estimated parameter on the time variable in the energy cost share demand equations is positive. This implies that technical progress is energy using.

Before proceeding further, I believe it may be useful to provide some interpretation on what is meant by input-using or input-saving technical progress. When technical progress occurs, the same amount of output can now be produced using fewer total inputs. The proportional savings on some inputs,

however, might be larger than for other inputs. Technical progress is said to be input i -using (input i -saving) if the proportional savings on the i th input is less than (greater than) the average proportional savings over all inputs, respectively. Finally, technical progress is said to be input i -neutral if the proportional savings on the i th input just equals the average proportional savings over all inputs. Since the estimated coefficient on the time variable in most of Jorgenson's energy cost share demand equations was positive, this implied that technical progress was energy-using.

Although the intuition is not completely obvious, it turns out that when technical progress is input i -using (i -saving), increases in the relative price of the i th input result in a lower (higher) rate of multifactor productivity growth. While this is essentially a mathematical result, its implications are very important. In particular, Jorgenson's finding that in virtually all sectors of the U.S. economy, technical progress is total energy using implies that increases in the relative price of energy forms, other things equal, result in reduced MFP growth.¹⁰ Moreover, similar findings have been reported by Berndt-Hesse [1986] using data for the manufacturing sectors of nine OECD countries, 1960-81; the Berndt-Hesse findings are also significant in that one of Jorgenson's other key assumptions -- that capital plant and equipment adjusts entirely within one year to price changes -- was relaxed by Berndt-Hesse.

The Jorgenson biased technical change findings highlight some very important but difficult questions. Among them are the following: Just how has disembodied technical progress affected demand for energy? What types of engineering examples correspond with this econometric finding? How can one interpret the additional econometric finding of Jorgenson that the input-using bias is larger for non-electric energy than for electric energy? Do Jorgenson's

findings based on a disembodied technical progress specification have any relationship to the Schurr hypothesis, which involves the interaction of embodied and disembodied technical progress? As of this point in time, our understanding of the energy-using biased technical progress hypothesis is still rather weak.

III.C. ELECTRIFICATION AND THE QUALITY OF AGGREGATE ENERGY

After World War II and until the late 1960's it was commonly believed that economic growth in the U.S. since 1929 was due primarily to technical progress. The stylized fact taught in most economics courses was that about 10% of growth in output was due to growth in input, and the remaining 90% was unexplained and therefore thought to be due to technical progress.

In a pioneering article, Dale Jorgenson and Zvi Griliches [1967] challenged this conventional wisdom, arguing that previous analysts failed to account properly for input quality changes. More specifically, they first argued that labor input had changed considerably over time, for by the late 1960's the average worker was more highly educated and more productive than he/she was two decades earlier.¹¹ Jorgenson-Griliches therefore developed a new measure of labor input that accounted for changes over time in educational attainment, and then called this new labor input measure a quality-adjusted labor input.

Similarly, Jorgenson-Griliches also argued that traditional measures of capital input failed to account properly for quality change. In particular, they argued that since 1945, the composition of capital investment changed considerably away from non-residential structures and toward producers' durable equipment. Since the economic life of structures is typically much longer than that for equipment, a dollar spent in year t on acquiring new equipment would yield more services that year than a dollar spent in year t on acquiring new

buildings or structures. This implied that the aggregate capital input measure should reflect the effects of the changing composition, for neglecting this would fail to account for the increased services yielded by the on average younger capital stock. Jorgenson-Griliches then went on to develop a new measure of capital input, and called it a quality-adjusted capital input.¹²

The result of these two input quality adjustments on the measurement of the role of MFP growth was enormous. Although some controversy ensued, by the early 1970's it had become clear that for the US since World War II, about 50% (rather than 10%) of growth in output was due to growth in input, and the remaining 50% (rather than 90%) was due to disembodied technical progress.

While the above discussion is of interest, the reader may wonder what its relationship is to energy usage. As I shall now argue, the issues underlying the adjustment of energy input for quality change over time are completely analogous to those underlying the adjustment of labor and capital inputs. In particular, one could measure aggregate energy input over time by a physical measure such as tons of coal equivalent, or British thermal units, just as one could measure labor input in terms of live bodies at work. Such measures would, however, fail to account for quality change over time.

Already in 1960 Schurr and Netschert had recognized the importance of input quality change over time, not just for labor, but also for energy. For example:

"The composition of the labor force has changed, and so has the composition of the fuel and power basket. Workers are, in general, better educated, and, similarly, certain energy commodities in use today are an improvement over those used seventy-five years ago (a kilowatt hour is, in this sense, a pound of coal with a college education)."

Schurr-Netschert [1960], p. 173.

There is of course a long literature on measuring the quality of energy, where quality has a clear thermodynamic foundation involving its availability to

do work. Within that literature, it is well-known that electricity has a very high quality. Following Schurr-Netschert, here I will use the phrase "energy quality" in a more general manner, and simply note that this usage is not inconsistent with the implications of thermodynamics.

In essence, the changing composition of energy toward electricity and away from first the solid fuels, and more recently, the liquid fuels, implies that the average quality of aggregate energy has improved over time, and that this quality change should be incorporated into MFP growth calculations. One possible way of doing this, which may elicit sympathy from some engineers, is to compute an aggregate measure for energy in which electricity is weighted by the average number of British thermal units used to generate a kilowatt hour. If this were done, electricity input today would be weighted by approximately 10,000 Btu's per kilowatt hour, instead of the common 3412 Btu's per kilowatt hour procedure based on their mechanical equivalence; for periods earlier in this century when electricity generation was less efficient, the weight would be approximately 20,000 Btu's per kilowatt hour. One problem with such a procedure is that it does not really deal well with electricity generated by hydropower or nuclear energy. A preferable procedure, and significantly, one based very firmly in the economic theory of index numbers, is to weight the various types of energy by their prices, for in this way their marginal value to users is quantified.¹³

In order to obtain a quantitative notion of how important it is to quality-adjust energy input, in Table 1 below I present several alternative measures of energy input in the manufacturing sectors of the U.S. and Japan. These figures are taken from Berndt, Sagawa, Sawa and Wood [1986].

As seen in the columns with the heading "Physical Energy Intensity" (defined as a Btu measure of aggregate energy divided by real output, and

indexed to 100 in 1974), in the US the traditional engineering measure of energy intensity declined only very slightly from 1965 to 1973, then dropped much more dramatically (at an average annual growth rate -- AAGR -- of 3.70%) following OPEC-I. Over the entire 1965-81 time period, physical energy intensity (average physical energy productivity) decreased (increased) at an AAGR of 1.96%.

While numbers such as these are often used to herald energy conservation gains in the US, they can be misleading in that the average quality of energy (where the component energy types are weighted by their prices, not their relative Btu contents) has increased. In choosing their energy inputs, firms are increasingly moving to higher quality energy types. This implies that quality-adjusted energy intensity has not fallen as rapidly as traditional physical measures of aggregate energy intensity. From 1965 to 1973 in the US, the AAGR in energy quality was 0.35%, and this increased substantially to 1.23% from 1974 to 1981; over the entire 1965-81 time period, energy quality in U.S. manufacturing increased at an AAGR of 0.81%.

Once one properly accounts for the improved energy quality, therefore, the apparent gains in energy conservation for the U.S. are not as large as commonly stated. This is not to be interpreted negatively, but simply indicates that manufacturing firms are increasingly turning toward the economically more efficient electricity and away from the liquid fuels. In the US, for example, the economic energy intensity (or, quality-adjusted energy intensity) declined 0.21% from 1965 to 1973, and then dropped much more sharply with an AAGR of 2.53% from 1974 to 1981. Over the entire 1965-81 time period, average energy intensity adjusted for quality change dropped at an AAGR of 1.17%. What this implies, therefore, is that about 40% of the apparent gains in energy conservation since 1965 in the U.S. are in fact due to improvements in energy quality.

Table 1

Physical and Quality-Adjusted Measures of Aggregate Energy Intensity
in the Manufacturing Sectors of the U. S. and Japan (1974=100)

Year	United States			Japan		
	Physical Intensity	Energy Quality	Economic Intensity	Physical Intensity	Energy Quality	Economic Intensity
1965	105.4	95.7	100.9	101.7	105.3	107.1
1966	105.1	95.7	100.6	103.0	101.3	104.3
1967	105.8	96.9	102.5	94.7	103.2	97.7
1968	107.7	96.7	104.1	92.3	102.5	94.6
1969	110.0	96.7	106.4	93.5	99.3	92.8
1970	112.8	96.8	109.2	92.4	98.9	91.4
1971	115.0	95.9	110.3	90.0	100.1	90.1
1972	109.5	97.0	106.2	91.4	100.3	91.7
1973	104.3	98.4	102.6	100.9	98.2	99.1
1974	100.0	100.0	100.0	100.0	100.0	100.0
1975	104.0	101.9	106.0	95.1	103.2	98.1
1976	97.7	104.0	101.6	93.0	104.4	97.1
1977	91.4	106.7	97.5	90.6	105.4	95.5
1978	86.6	107.8	93.4	87.1	106.8	93.0
1979	85.1	106.6	90.7	82.7	108.4	89.9
1980	81.6	107.6	87.8	77.9	110.4	86.0
1981	76.8	108.9	83.6	69.4	111.7	77.5
1982				63.8	113.7	72.5
1983				60.5	116.7	70.6
AAGR						
1965-81	-1.96	0.81	-1.17	-2.36	0.37	-2.00
1965-73	-0.13	0.35	-0.21	-0.10	-0.87	-0.97
1974-81	-3.70	1.23	-2.53	-5.08	1.59	-3.58
1974-77	-2.95	2.18	-0.84	-3.24	1.77	-1.52
1978-81	-3.92	0.34	-3.63	-7.29	1.51	-5.90
1982-83				-5.17	2.64	-2.62

Notes: Physical intensity is aggregate energy in Btu equivalents divided by output. Energy quality is the economic price-weighted aggregate of energy divided by the Btu aggregate of energy. In both the above Btu calculations 1 kilowatt hour of electricity = 3412 Btu's. The economic intensity is the product of the first two columns. AAGR is the average annual growth rate. Source: Berndt, Sagawa, Sawa and Wood [1986].

For Japan, energy quality improvements are also very important, especially since 1974. As seen in the second set of columns in Table 1, from 1965 to 1973 the index of physical energy intensity stayed at roughly the same level (although it dropped until 1968 and then rose until 1973). From 1974 to 1981, however, the physical energy intensity fell at a rate of slightly larger than 5% per year, compared with the 3.7% rate of decrease in the U.S. This 5% drop per year in physical energy intensity continued in Japan through 1982 and 1983.

While the physical energy intensity measure is of interest, as noted earlier it masks important compositional changes in energy consumption that affect aggregate energy quality. In Japan, interestingly, average energy quality actually dropped from 1965 to 1973 (unlike the US), but since 1974 the role of energy quality changes has been almost identical in Japan and the US.

Specifically, for Japan over the 1974-81 time period, while physical energy intensity dropped at an AAGR of 5.08%, energy quality increased at an AAGR of 1.59%, implying that the economic energy intensity fell at approximately 3.58% per year. Hence for Japan, energy quality improvements resulted in about a 33% reduction in apparent energy conservation gains (the latter based on physical weights). For the US, the corresponding growth rates during the same 1974-81 time period are -3.70% for physical energy intensity, 1.23% for energy quality increases, and -2.53% for economic energy intensity. This implies that since 1974 in the US, as in Japan, the relative role of energy quality improvements was about 33% -- improvements in energy quality reduced apparent energy conservation gains by about one-third. Notice also that for Japan, in the last two years of the sample (1982-83) the energy quality proportion increases to over 50%.

In summary, therefore, the changing composition of energy inputs in the manufacturing sectors of the US and Japan toward electricity and away from the

liquid fuels has resulted in an increase in the average quality of the aggregate energy input. This more effective, more productive aggregate energy input should be properly accounted for when undertaking average energy and MFP growth calculations.

III.D. ENERGY PRICE SHOCKS AND THE QUALITY OF CAPITAL: MEASUREMENT ISSUES

The fourth and final example of the special relationship among energy usage, technical progress and productivity growth concerns the impacts of unexpected energy price changes. Essentially, the argument here is that when energy price shocks occur, utilization rates of the various surviving vintages of capital adapt, and as a result the flow of services per unit of capital stock is altered. Such changes in the flow/stock relationship are unlikely to be uncovered by traditional measures of capital input, and as a result, since MFP growth is computed as growth in output minus growth in aggregate input, MFP growth will be incorrectly measured. The implications of this measurement issue are not trivial. If, for example, growth in real capital input is overstated since 1973 due to utilization reductions, then so too would be the growth of aggregate input; as a consequence, growth in the MFP productivity residual would be understated. Some background comments might be of help here.¹⁴

In the short-run, the services available from capital equipment are largely fixed, and so too are the operating characteristics of the equipment. Although considerable energy-capital substitutability is possible ex ante, once capital is put into place the ratio of energy consumption to capital services actually utilized is fixed. The relationship between energy and utilized capital services is then one of putty-clay -- malleable ex ante, fixed ex post.

This ex post fixity is extremely important, for it implies that when firms make decisions concerning the optimal energy efficiency for long-lived capital

equipment they are about to purchase, expectations of future relative energy prices over the likely lifetime of the asset are critical. In a very important sense, therefore, at any point in time the various surviving vintages of capital equipment each embody an energy efficiency reflecting the relative energy price expectations prevailing when the equipment was originally acquired.

Even though ex post fixity is common for energy use, dramatic changes in operating costs may alter the pattern of utilization across differing capital vintages embodying varying operating characteristics, decreasing in particular the utilization of energy inefficient vintages relative to the more efficient ones. Scrapping plans may also be changed, accelerating the scrapping of energy inefficient equipment. As investment occurs and some of the energy-inefficient vintages are gradually replaced, the patterns of utilization across vintages adapt as well.

If this view is correct, then the energy price increases of the 1970's altered vintage-specific utilization rates, and thus changed the relationship between the flow of capital services and the stock of capital. Since the traditional procedure for measuring the flow of capital services in a given period involves first estimating the capital stock (adjusting for inflation) and then assuming a fixed proportionality over time in the ratio of service flows to stocks, the conventional procedure cannot accommodate the effects of energy price-induced variations in the proportionality factor between service flows and capital stocks.

Impressive features of this hypothesis are that, (i) it is completely consistent with the historical evidence of a slow and gradual, rather than instantaneous improvement in energy efficiency since 1973, (ii) it is consistent with the sluggish turnover of energy-inefficient capital plant and equipment

that accelerated during the OPEC-II epoch in most OECD countries, and (iii) it may also be consistent with the dramatic changes that occurred in the post-OPEC stock market valuations of capital in energy-using sectors such as manufacturing. Moreover, since this hypothesis involves interactions between capital and energy inputs, it highlights the complex and important relationships among energy, capital utilization, investment, embodied technical progress, and measured MFP growth.¹⁵

All this is very plausible, but how important is it empirically? Somewhat surprisingly, the empirical research to date attempting to quantify this capital measurement error has yielded only modest results. Berndt and Wood [1986a,b] report, for example, that for the US manufacturing sector the post-OPEC slowdown in multifactor productivity growth may have been overstated by as much as 20%, while for the UK the estimated magnitude is less than half that. Such measurement error numbers are substantial, but they also indicate that our knowledge concerning causes of the MFP growth slowdown of the 1970's (and back perhaps as far as 1965) is still disappointingly small.¹⁶

IV. CONCLUDING REMARKS

In this paper I have attempted to survey and interpret several of the most important economic aspects underlying the relationships among technical progress, productivity growth and energy use. I began by focusing on the economic theory of cost and production, distinguished factor-specific from MFP growth, and embodied from disembodied technical progress.

I then briefly summarized the most salient empirical regularities of the last few decades, and noted in particular that quite frequently the factor-specific and MFP growth measures moved in different ways, implying that one should be cautious about talking about "the" productivity growth slowdown.

In the second half of the paper, I focused on the special role of energy consumption in inducing and reflecting the effects of technical progress and productivity growth. Four examples were chosen to highlight the special role of energy: (i) the Schurr electrification hypothesis, which dramatizes the interactive nature of embodied and disembodied technical progress; (ii) the biased technical change hypothesis, which depends critically on disembodied technical progress, but whose underlying engineering interpretation is not yet clear; (iii) the energy quality issue, which highlights the fact that not all British thermal units are identical, and that the changing composition of energy towards electricity in the last few decades implies that physical measures of aggregate energy input should be adjusted for quality change; and (iv), the energy price-induced change in utilization of capital plant and equipment issue, which points to the importance of the fixity of capital plant and equipment, and tends to result in overstatements of the MFP growth slowdown after 1973.

While the four examples are varied, they contain a common theme which is worth noting once again. In thinking about relationships among energy usage, technical progress and productivity growth, I believe three concepts are indispensable: embodiment, diffusion and learning. It is an understatement to note that economists do not have an intellectual monopoly on these concepts. While economic thinking can contribute significantly to understanding the forces linking energy usage, technical progress and productivity growth, economists have a great deal to learn from colleagues in the engineering and physical sciences, from those in other social sciences, and from historians.

FOOTNOTES

¹Discussions of these explanations have been presented and surveyed by, among others, Lindbeck [1983], Maddison [1987], Mork [1988] and Olson [1988].

²For a more detailed discussion of factor-specific and multifactor productivity growth in the context of cost and production functions, see Berndt [1978,1980] and Berndt-Fuss [1986].

³For more detailed discussions of the notions of embodied and disembodied technical progress, see Solow [1957,1960].

⁴The classic analytical study of the effects of learning on production and costs is that by Arrow [1962]. For additional discussion of learning curves, and more extensive historical references, see chapter 3 in Berndt [1990].

⁵Denison reports, however, that this temporal coincidence is to some extent a result of aggregation. When quarterly rather than annual series are employed, BLS data suggest that the 1973-74 slowdown in labor productivity slightly preceded the rise in oil prices from OPEC I. For further discussion, see Denison [1985], pp. 52-56.

⁶See "News: Productivity and Costs", a regular publication of the US Department of Labor, Bureau of Labor Statistics, Washington, DC 20212.

⁷In addition to the original classic study by Schurr-Netschert [1960], a number of other researchers have examined various aspects of the Schurr hypothesis. Included among such studies are Berndt [1986], Devine [1983a,b;1984], DuBoff [1966,1967], Jorgenson [1986], Rosenberg [1983], Schurr [1982,1984] and Woolf [1980,1983,1984,1987].

⁸The first publication in this literature is Jorgenson-Fraumeni [1981], in which energy was treated as an aggregate; also see Jorgenson [1988]. In subsequent work such as Jorgenson [1984,1986], energy is disaggregated into electric and non-electric energy.

⁹To some extent, of course, the price deflators for new investment goods incorporate "quality change". On this, see Griliches [1971], chapter 4 in Berndt [1990], and Gordon [1990].

¹⁰The pattern of biased technical change is more diverse when energy is broken down into electric and non-electric energy; although no single pattern dominates, Jorgenson's most common finding is that the input-using bias is larger for non-electric than for electric energy.

¹¹Jorgenson and Griliches were not the first to attempt to measure labor quality in the productivity context (Denison had also done so), but their

framework was the first to do so in a symmetric manner for all inputs, within a consistent and rigorous theoretical framework based on the theory of cost and production.

¹²A major problem in measuring quality changes in capital input lie with the official government deflators used to measure real investment. For further discussion, see Griliches [1971], chapter 4 in Berndt [1990], as well as Gordon [1990].

¹³Index number issues, with particular emphasis on energy, are discussed in detail in Berndt [1978]. For a related application, see Marlay [1984].

¹⁴This argument has been called by some the "Baily hypothesis" (see Baily [1981]), and is presented in greater detail in Berndt-Wood [1984,1986a,b].

¹⁵In contrast to this short-run relationship between energy price shocks and measured capital input, a longer term relationship between energy prices and multifactor productivity involves energy-capital complementarity, in which energy price changes are found to reduce demands for both energy and capital. To the extent this is true and to the extent that new investment goods are the carriers of technical progress (due to embodiment), energy price increases could in the long run reduce the rate of MFP growth. Empirical evidence on the energy-capital complementarity hypothesis, and its implications for long-run productivity growth, is found in Berndt-Wood [1986a,b].

¹⁶A closely related issue concerns the effects of energy price shocks on the depreciation patterns and second-hand values of energy-using equipment with fixed energy efficiencies. Using data on various types of second-hand transactions for energy-using equipment, Hulten, Robertson and Wykoff [1989] find that energy price shocks had only a very small impact on the depreciation patterns and prices of such energy-using equipment.

REFERENCES

- Arrow, Kenneth J. [1962], "The Economic Implications of Learning by Doing," Review of Economic Studies, Vol. 29, June, pp. 155-173.
- Baily, Martin N. [1981], "The Productivity Growth Slowdown and Capital Accumulation," American Economic Review, Papers and Proceedings, Vol. 71, No. 2, May, pp. 326-331.
- Berndt, Ernst R. [1990], The Practice of Econometrics: Classic and Contemporary, Reading, MA: Addison-Wesley Publishing Company.
- Berndt, Ernst R. [1986], "Electrification, Embodied Technical Progress, and Labor Productivity Growth in U.S. Manufacturing, 1889-1939", chapter 3 in Sam H. Schurr and Sidney Sonenblum, editors, Electricity Use, Productive Efficiency and Economic Growth, Proceedings of a Workshop Sponsored by the Electric Power Research Institute, Palo Alto, CA: Electric Power Research Institute, pp. 93-114.
- Berndt, Ernst R. [1980], "Energy Price Increases and the Productivity Slowdown in United States Manufacturing," in The Decline in Productivity Growth, Proceedings of a Conference held in Edgartown, MA, June, Boston: Federal Reserve Bank of Boston, Conference Series No. 22, pp. 60-89.
- Berndt, Ernst R. [1978], "Aggregate Energy, Efficiency and Productivity Measurement," Annual Review of Energy, Vol. 3, pp. 225-273.
- Berndt, Ernst R. and Melvyn A. Fuss [1986], "Productivity Measurement with Adjustments for Variations in Capacity Utilization and Other Forms of Temporary Equilibrium," Journal of Econometrics, Vol. 33, No. 1/2, November, pp. 7-29.
- Berndt, Ernst R. and Dieter M. Hesse [1986], "Measuring and Assessing Capacity Utilization in the Manufacturing Sectors of Nine OECD Countries," European Economic Review, Vol. 30, No. 5, October, pp. 961-989.
- Berndt, Ernst R., Naoto Sagawa, Takamitsu Sawa and David O. Wood [1986], "Energy Intensity and Productivity in U.S. and Japanese Manufacturing Industries," paper presented at the Eight Annual North American Conference of the International Association of Energy Economists, Cambridge, MA., November.
- Berndt, Ernst R. and David O. Wood [1986a], "Energy Price Shocks and Productivity Growth in U.S. and U.K. Manufacturing," Oxford Review of Economic Policy, Vol. 2, No. 3, Autumn, pp. 1-31.
- Berndt, Ernst R. and David O. Wood [1986b], "Energy Price Shocks and Productivity Growth: A Survey," in Richard L. Gordon, Henry D. Jacoby and Martin B. Zimmerman, editors, Energy, Markets and Regulation: What Have We Learned, Cambridge, MA: MIT Press, pp. 305-342.

- Berndt, Ernst R. and David O. Wood [1984a], "Energy Price Changes and the Induced Revaluation of Durable Capital in U.S. Manufacturing during the OPEC Decade," M.I.T. Energy Laboratory Report No. 84-003, March.
- Berndt, Ernst R. and David O. Wood [1984b], "Electrification, Embodied Technical Progress, and Labor Productivity Growth Variations Among States in the U.S.: 1909, 1914 and 1919," paper presented at the Sixth Annual North American Meetings of the International Association of Energy Economists, San Francisco, California, November.
- Denison, Edward F. [1985], Trends in American Economic Growth, 1929-82, Washington, DC: The Brookings Institution.
- Devine, Warren D., Jr. [1984]. "Technological Change and Electrification in the Printing Industry, 1880-1930," Draft Final Report, Oak Ridge, TN.: Institute for Energy Analysis, Oak Ridge Associated Universities, April.
- Devine, Warren D., Jr. [1983a], "An Historical Perspective on the Value of Electricity in American Manufacturing," Research Memorandum ORAU/IEA 82-8(M), Oak Ridge, TN.: Oak Ridge Associated Universities, May.
- Devine, Warren D., Jr. [1983b], "From Shafts to Wires: Historical Perspectives on Electrification," Journal of Economic History, Vol. 43, No. 2, June, pp. 347-372.
- DuBoff, Richard B. [1967], "The Introduction of Electric Power in American Manufacturing," Economic History Review, Vol. 20, No. 3, Second Series, December, pp. 509-518.
- DuBoff, Richard B. [1966], "Electrification and Capital Productivity: A Suggested Approach," Review of Economics and Statistics, Vol. 48, No. 4, November, pp. 426-431.
- Gordon, Robert J. [1990], The Measurement of Durable Goods Prices, Chicago: University of Chicago Press.
- Griliches, Zvi, ed. [1971], Price Indexes and Quality Change, Cambridge, MA: Harvard University Press.
- Hulten, Charles R., James W. Robertson, and Frank C. Wykoff [1989], "Energy, Obsolescence, and the Productivity Slowdown," in Dale W. Jorgenson and Ralph Landau, eds., Technology and Capital Formation, Cambridge, MA: MIT Press, 225-258.
- Jorgenson, Dale W. [1988], "Productivity and Postwar U.S. Economic Growth," Journal of Economic Perspectives, Vol. 2, No. 4, Fall, pp. 23-41.
- Jorgenson, Dale W. [1986], "The Role of Energy in Productivity Growth," chapter 2 in Sam H. Schurr and Sidney Sonenblum, editors, Electricity Use, Productive Efficiency and Economic Growth, proceedings of a workshop sponsored by the Electric Power Research Institute, Palo Alto: Electric Power Research Institute, pp. 43-92.

- Jorgenson, Dale W. [1984], "The Role of Energy in Productivity Growth," The Energy Journal, Vol. 5, No. 3, July, pp. 11-26.
- Jorgenson, Dale W. and Barbara M. Fraumeni [1981], "Relative Prices and Technical Change," chapter 2 in Ernst R. Berndt and Barry C. Field, editors, Modeling and Measuring Natural Resource Substitution, Cambridge, MA: MIT Press, pp. 17-47.
- Jorgenson, Dale W. and Zvi Griliches [1967], "The Explanation of Productivity Change," Review of Economic Studies, Vol. 34 (3), No. 99, July, pp. 249-282. Reprinted with corrections in U.S. Department of Commerce, Survey of Current Business [1972], "The Measurement of Productivity," Vol. 52, No. 5, Part II, May, pp. 3-36.
- Kendrick, John W. [1983], "International Comparisons of Recent Productivity Trends," in Sam H. Schurr, ed., Energy, Productivity, and Economic Growth, Cambridge, MA: Oelgeschlager, Gunn and Hain, pp. 71-120.
- Lindbeck, Assar [1983], "The Recent Slowdown of Productivity Growth," Economic Journal, Vol. 93, No. 369, March, pp. 13-34.
- Maddison, Angus [1987], "Growth and Slowdown in Advanced Capitalist Economies," Journal of Economic Literature, Vol. 25, No. 2, June, pp. 649-698.
- Marlay, Robert C. [1984], "Trends in Industrial Use of Energy," Science, Vol. 226, No. 4680, 14 December, pp. 1277-1283.
- Mork, Knut Anton [1988], "The Boom that Wasn't: Evidence From 1986-87 on the Macroeconomic Effects of Oil Price Fluctuations," Vanderbilt University, unpublished manuscript.
- Norsworthy, J. Randolph, Michael J. Harper and Kent Kunze [1979], "The Slowdown in Productivity Growth: Analysis of Some Contributing Factors," Brookings Papers in Economic Activity, 2:1979, pp. 387-421.
- Olson, Mancur [1988], "The Productivity Slowdown, The Oil Shocks, and the Real Cycle," Journal of Economic Perspectives, Vol. 2, No. 4, Fall, pp. 43-69.
- Rosenberg, Nathan [1983], "The Effects of Energy Supply Characteristics on Technology and Economic Growth," in Sam Schurr, Sidney Sonenblum and David O. Wood, eds., Energy, Productivity and Economic Growth, Cambridge, MA.: Oelgeschlager, Gunn and Hain.
- Schurr, Sam H. [1984], "Electricity Use, Technological Change and Productive Efficiency," Annual Review of Energy, Vol. 9, pp. 409-425.
- Schurr, Sam H. [1982], "Energy Efficiency and Productive Efficiency: Some Thoughts Based on American Experience," Energy Journal, Vol. 3, No. 3, July, pp. 3-14.
- Schurr, Sam H. and Bruce C. Netschert [1960], Energy in the American Economy, 1850-1975, Baltimore: Johns Hopkins Press for Resources for the Future.

- Solow, Robert M. [1960], "Investment and Technical Progress," ch. 7 in Kenneth J. Arrow, Samuel Karlin and Patrick Suppes, eds., Mathematical Methods in the Social Sciences, 1959: Proceedings of the First Stanford Symposium, Stanford: Stanford University Press, pp. 89-104.
- Solow, Robert M. [1957], "Technical Change and the Aggregate Production Function," Review of Economics and Statistics, Vol. 39, No. 5, August, pp. 312-320.
- Tinbergen, Jan [1942], "Zur theorie der langfristigen wirtschaftsentwicklung," Welwirtschaftliches Archiv, Band 55:1, pp. 511-549. English translation, "On the Theory of Trend Movements," in Jan Tinbergen: Selected Papers, L. H. Klassen, L. M. Koyck and H. J. Witteveen, editors, Amsterdam: North Holland, 1959.
- Woolf, Arthur [1987], "The Residential Adoption of Electricity in Early Twentieth Century America," Energy Journal, Vol. 8, No. 1, January, 19-30.
- Woolf, Arthur [1984], "Electricity, Productivity, and Labor Saving: American Manufacturing 1909-1929," Explorations in Economic History, Vol. 21, April, pp. 176-191.
- Woolf, Arthur [1983], "Energy Substitution in American Manufacturing: A Look Backward," unpublished manuscript, Department of Economics, University of Vermont, Burlington, July.
- Woolf, Arthur [1980], "Energy and Technology in American Manufacturing: 1900-1929," unpublished Ph.D. dissertation, University of Wisconsin-Madison, Department of Economics, October.