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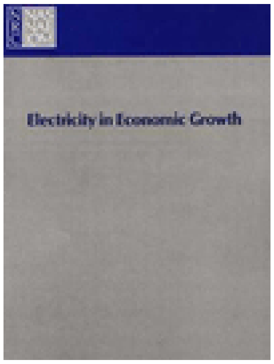

Electricity in Economic Growth

Committee on Electricity in Economic Growth, Energy Engineering Board, National Research Council

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Electricity in Economic Growth

A Report Prepared by the

Committee on Electricity in Economic Growth
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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Preface

This study of electricity and economic growth originated from the need of the U.S. Department of Energy to understand more fully the complex relationships between economic activity and electricity use. Such understanding is basic to policy and program decisions about legislation, research, and incentives for the private sector.

The objectives of the study were twofold. The first was to show how trends in the growth of electricity demand may be affected by changes in the economy. The second was to examine the connection between the use of electrotechnologies and productivity. The influences of prices and regulatory measures on electricity demand are acknowledged in the report, but the substantial analyses and projections needed to address these effects had to be left for other studies. Similarly, we did not try to build new models of electricity demand, make demand forecasts, estimate the best mixes of supply technologies, or address specific policy recommendations that might influence electricity supply and demand.

We reviewed literature our members knew to be relevant and heard briefings by experts who had conducted research on electricity in the economy. Other experts briefed the committee on specific uses and technological trends in the manufacturing, commercial, and industrial sectors.

The report is intended for officials in the Department of Energy concerned with policy analysis and planning, federal and state regulatory officials, and managers of electric utilities. Members of the broader public concerned with energy, electricity, and conservation will also find information of interest here.

It is a pleasure to recall the interest and support of Ronald J. Sutherland of Los Alamos National Laboratory and of David H. Meyer, Howard H. Rohm, and Edward F. Mastal of the U.S. Department of Energy, all of whom were concerned with the sponsorship of the study. All the members of the committee gave generously of their time and experience. Nor would the task have been completed without the constant support of Dennis F. Miller, Executive Director of the Energy Engineering Board, who was responsible for the concept of the study. Cheryl A. Woodward handled the manifold administrative and logistic matters with a competence and graciousness admired by all. John M. Richardson, of the board's staff, deserves special commendation for his efforts in support of the committee's work, including, but not limited to, his assistance in synthesizing and integrating the written material of the committee, the direction and continuity he provided throughout the project, and his warm and cheerful demeanor in the pursuit of the committee's business. I acknowledge all these contributions with sincere thanks.

MARTIN BAUGHMAN, CHAIRMAN
COMMITTEE ON ELECTRICITY IN ECONOMIC GROWTH

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Summary

From 1973 through 1982 a number of general trends that previously characterized electricity use showed distinct changes. Such changes have given rise to significant uncertainty about the future relationship between electricity use and economic growth. It is therefore useful to examine the forces that now underlie electricity use and to ask whether basic changes have occurred or are occurring, and, if so, to determine what we can about their nature and extent.

We address two fundamental relationships between electricity use and the economy in this report. One is how electricity use depends on various economic and technical factors, that is, the demand for electricity, to use the term of economics. The second is to what extent applications of electricity, as an especially high grade of energy, may facilitate technological advances and stimulate the economy through productivity gains. How electricity should be supplied we leave for others to analyze.

Ordinary experience indicates that electricity use should depend at least in part on the general level of economic activity, the prices of electricity and its alternatives, public policy, regulation, and the development and diffusion of novel and more efficient applications.

It is important to understand the relationships between electricity use and the economy, regarding both consumption and productivity, to formulate public policy, regulate the industry, and manage individual firms. Public policies may need to encourage change in the system's operation through legislation, regulatory changes, investment incentives, or research. Better knowledge of the relationships between electricity use and the economy, both in the aggregate and for particular end uses, should permit better regulatory decisions to facilitate economic efficiency. The management decisions of individual utilities and their suppliers will of course also benefit from a better framework for analysis of their business choices.

The committee's task was to assess the role of electricity in domestic economic growth. Our charge was to review the historical importance of electricity in U.S. economic growth, analyzing structural economic changes that have or may take place and that could influence the future growth of electricity use and reviewing recent changes in electricity use with attention to their significance for the future. We did not construct new models or make particular forecasts.

RECOMMENDATIONS

We discuss the conclusions supporting our recommendations more fully below and in Chapter 1. In brief, two important conclusions underlie the recommendations that follow. First, there has been a strong correlation between the use of electricity and the size of the gross national product. Second, the recent research described in Chapter 3 was judged sufficiently significant to say with some confidence that there is a strong connection between electricity and productivity growth.

1. *The relationship between electricity and productivity is so important that it should be considered in developing federal and state energy and economic policies*.

   Productivity growth is critical in attacking many problems facing the United States, including the federal deficit and the balance of trade. Consequently, all possibilities of stimulating productivity growth, including attention to electricity supply and use, should be evaluated and pursued in accord with their promise.

   * * * * *

2. *To foster increased productivity, policy should stimulate increased efficiency of electricity use, promote the implementation of electrotechnologies when they are economically justified, and seek to lower the real costs of electricity supply by removing any regulatory impediments and developing promising technologies to provide electricity*.

   The findings of this report establish a connection between electricity and productivity growth when two factors coexist: technical change and favorable electricity supply conditions. In addition, cost-effective increases in the efficiency of electricity use will themselves not only increase productive output for a given input of electricity but also free income for other purposes. These points suggest that federal and state policies that promote lowering the real costs of electricity supply and use, through research and development and through more efficient pricing by regulatory authorities, will benefit productivity growth.

   * * * * *

3. *Further research should be undertaken to identify and quantify the forces affecting the relationships between electricity and economic growth in view of their critical importance, complexity, and regional diversity*.

   The strong and persistent relationship between electricity use and gross national product requires that close attention be paid to the adequacy of electricity supply to sustain a high future rate of economic growth. The adequacy of electricity supply can be maintained not only through new generation facilities but also through efficiency improvements that use existing generating capacity better. Although favorable electricity supply conditions of themselves will not assure economic growth, a lack of

> adequate supply would almost certainly constitute a serious impediment to such growth. We need to learn more about the correlations and causal relationships between economic growth and the use of electricity. Well-directed policy, regulatory, and managerial decisions rest on such knowledge.

CONCLUSIONS

For the reader's convenience our principal conclusions, along with brief supporting rationale, are given here and are covered more fully in Chapter 1.

Electricity Consumption

Electricity use and gross national product have been, and probably will continue to be, strongly correlated.

In this century there have been four well-defined periods in the relationship between electricity use and gross national product, periods in which the relationship has been linear and stable. The fourth period began after World War II and may still be continuing, although the character of the relationship following the 1973 Arab oil embargo is in dispute. It is not yet possible to conclude whether changes in the data after 1973 reflect only variations from the most recent trend line, as have occurred before, or whether they indicate a fundamental shift in the relationship. Regarding the future course of the relationship, no reasons yet seem likely either to compel a change or to inspire great confidence that past trends will continue. Hence the strongest statement that can be made is that the continuation of the long-term correlation is probable.

Historic trends in the relationship between electricity use and gross national product include the effects of a host of factors not explicitly identified in the simple linear equation relating the two variables. Factors believed to be important include the prices of electricity and of competing energy forms, the composition of national output, shifts in regional economic activity, technical change, conservation, and government policies. Other representations of the relationship may be used to analyze such factors more fully. However, it is only when there are major changes in these underlying variables that we should expect changes in the fundamental relationship between electricity use and gross national product. Even then some effects may cancel each other (such as rises in both electricity and other energy prices). Two forces believed important in determining the basic trend of future relationships between electricity use and economic activity are the introduction of electrotechnologies and conservation. However, their future effects, like those of other underlying variables, are not readily quantified.

Electricity and nonelectrical energy prices are generally acknowledged as factors determining electricity consumption. However, by far the most important contribution to explaining consumption in the past has been gross national product. The observed departure on occasion of electricity consumption from the main trend line may be explained in part by taking price changes into account. Furthermore, there is an implicit dependence of electricity consumption on energy prices through the dependence of gross national product in part on productivity growth, which in turn is shown to depend partly on energy prices.

Productivity Growth

Productivity growth may be ascribed partly to technical change; in many industries technical change also tends to increase the relative share of electricity in the value of output, and in these industries productivity growth is found to be the greater the lower the real price of electricity, and vice versa.

Economic growth, conveniently expressed as percentage change in gross national product, results from growth in capital input, labor input, and productivity. Productivity represents increases in output that are not accounted for by contributions of the first two factors. Productivity growth for the economy as a whole derives mainly from sectoral productivity growth.

The decline in the rate of U.S. economic growth since the early 1970s is associated with a decline in sectoral productivity growth rates, rather than other factors, and is strongly associated with increased energy prices.

These associations were established by an econometric model, which shows that the relationships among technical change, price, and productivity growth are such that, for many industries, technical change in combination with low electricity prices drives up overall productivity growth, and conversely. Regarding nonelectrical energy, such effects are found in even more industries.

The decline in the real cost of electricity, in part due to dramatic increases in the thermal efficiency of electricity generation, increased electricity use and stimulated productivity growth until the early 1970s. The rise of electricity costs, combined with a rise in the prices of primary fuels after the international oil price increases of 1973 and 1979, has been a factor in reduced productivity growth in many industries, which may partly be explained by the substitution of other, less efficient inputs for these energy inputs.

Technical Change

Technical change has made possible many new opportunities for exploiting the special qualities of electricity. In the past these changes were often associated with increased intensity of electricity use, but in the future their net effect on that intensity will depend on the balance between their increased penetration and the increased efficiency of these applications.

Electricity has unique properties that make it an attractive form of energy: its highly ordered nature, its flexibility, and its cleanliness. There is still a large potential for further electrical applications that take advantage of these special properties.

Some electrotechnologies increase the intensity of electricity use (electricity use per unit of economic output, or electricity intensity) through wider application of electrical processes; others decrease it through productivity gains. In the economy as a whole the increase in electricity intensity with increased gross national product has proved to be relatively small because of these offsetting effects.

Historically, technical change exploiting the special qualities of electricity has contributed to increased productivity and thereby to increases in gross national product. We can expect this trend to continue.

The Effects of Price Changes

Electricity prices and alternative fuel prices affect electricity consumption in two ways: first, they directly affect the use of electricity and nonelectric fuels as input factors of production; second, they indirectly affect productivity growth and thereby economic growth.

If electricity prices alone rise, electricity use will decrease according to its elasticity of demand with respect to its own price. A rise in the price of competing fuels, without a rise in the price of electricity, will increase electricity consumption through elasticity of demand with respect to the prices of other fuels. If electricity prices rise because of a rise in primary fuel prices, a reduction in electricity use through own-price elasticity will occur and will be offset to some degree by an increase in the use of electricity instead of primary fuels, that is, through cross-price elasticity.

Any increase in the real price of electricity will also indirectly further decrease its use because it will lower productivity growth rates in many industries, in turn leading to a lowered rate of general economic growth.

Conservation

There is further potential for increasing the efficiency of electricity use, particularly in the residential and commercial sectors.

Particularly in the residential and commercial sectors, efficiency improvements can be made economically in both new construction and existing buildings under the incentive of higher energy prices. These improvements would reduce the intensity of electricity use. On the other hand, such reductions could be offset by new uses of electricity in production and household applications. In addition, some established electricity applications, such as air conditioning and electric space heating, still show potential market growth.

Efficiency improvements through conservation and load management can also benefit economic growth by reducing the long-term costs of electricity supply, and thus the price of electricity.

Composition of National Output

Changes in the composition of national output toward less electricity-intensive goods and services have been offset by growth in the intensity of electricity use within all the major use sectors so that the combined effect on electricity demand growth has not yet been great. However, if the trend toward a leveling off in sectoral electricity intensity growth that began in the late 1970s continues, future shifts toward less electricity-intensive goods and services are likely to dampen electricity demand growth relative to national output.

Since 1950 the share of gross product originating in the commercial sector has increased steadily, while that in the industrial sector as a whole has declined. The electricity intensity of the industrial sector is about three times that of the commercial sector so that shifts away from industry, other things being equal, would lead to a decline in electricity intensity for the total economy.

There were large increases in average electricity intensity within all consuming sectors after World War II that more than counteracted the negative influences on overall intensity from intersectoral shifts. However, almost all of the growth in average sectoral intensity occurred prior to 1973. By 1983 industrial and commercial sector electricity intensities were back near their values in 1973, and residential electricity intensity remained at about its 1977 value. It is not yet clear whether these recent declines in sectoral electricity intensity growth represent a new long-term trend or only short-term responses.

Regional Differences

Valid conclusions about electricity demand drawn from national data do not necessarily pertain to regional circumstances; there are significant regional differences in such factors as economic output, prices, electricity supply mix, availability of generating capacity, climate, and regulatory environment.

Regarding economic activity, the regional factors important to electricity consumption include overall output, industry mix, labor and resource availability, and the relative importance of a region's commercial and industrial sectors. Regarding energy use, important regional factors include electricity and nonelectrical energy prices, electricity supply mix, climate, and regulation. National policy decisions should be sensitive to these regional differences.

1

Introduction, Conclusions, and Recommendations

INTRODUCTION

From 1973 through 1982 a number of the general trends that characterized electricity use between 1960 and 1972 showed distinct changes. The annual percentage change in electricity price, adjusted for inflation, reversed direction, from a decrease of 3.8 percent per year to an increase of 4 percent per year. The price of a unit of electric energy fell from about 7 to about 3 times the price of an equivalent amount of energy in the form of natural gas and heating oil, because of the rise in the price of fossil fuels. The rate of growth in electricity use dropped from 7 to 2 percent per year; and although formerly it had exceeded real growth rate of gross national product (GNP), the growth rate fell to approximately the same pace as that of GNP.

Such changes have led to great uncertainty about the future relationships between electricity use and economic growth. It is therefore necessary to examine the forces that now underlie electricity use and to ask whether basic changes have occurred or are occurring, either in kind or degree.

Two Important Relationships

Two important relationships between electricity use and the economy are addressed in this report. One is how electricity use, or demand, in the usual sense of economics, depends on various economic and technical factors. The second is how electricity, as an especially high grade of energy, may facilitate technological advances, and in turn stimulate the economy, by providing gains in productivity. Our report does not address the question of electricity supply—that is, which generation technologies in what combinations should be used to serve demand.

Ordinary experience suggests that electricity use should depend on the general level of economic activity, the prices of electricity and its alternatives, public policy, the regulatory environment, and the development of novel applications, among other factors. Let us look briefly at each of these.

- General economic activity is usually represented by GNP. For detailed analysis it is often important to disaggregate GNP into sectoral components and to make other disaggregations by geography and demography as well. In particular, there are important regional differences in providing and using electricity.
- Electricity prices depend mainly on investment requirements for all types of plant and equipment, interest rates, fuel costs, and allowed rates of return. All these cost elements have varied more since 1972 than they did previously, generally leading to higher electricity prices.
- The price of fossil fuels rose even more dramatically than that of electricity during the 1970s. Thus, the price of electricity was relatively attractive compared to available alternatives, leading to a growth in electricity use. On the other hand, since the cost of electricity generation depends in part on the cost of fossil fuels, the price trends made increased efficiency of electricity use, and sometimes avoidance of use, more desirable than before. The price trends also led to the search for less expensive ways of producing with available technologies and for other methods of generation, such as co-generation, wind power, and solar electric power, in the hope of finding less expensive alternatives.
- Public policy, implemented in various ways at various levels of government, can also influence electricity consumption. Some policies act directly, such as those that control prices or that provide incentives for conservation. Other policies act indirectly, such as import restrictions and tax preferences for research and development. Thus the effect of public policy may be felt through factors such as prices, regulations, and the growth of new applications for electricity. It is certainly possible to model the effect of any particular policy, but the net effect of many may be hard to estimate.
- Regulatory constraints influence electricity use, usually through their effects on price. Regulation may encourage consumption by keeping prices down, or it may impose added costs to satisfy requirements for operational safety and environmental protection. Regulation may create other kinds of barriers to use by limiting the siting and construction of generating capacity.
- Novel applications for electricity, such as the electric furnace for steelmaking, are often developed as one aspect of ongoing technical change of all sorts. Such applications are adopted when they lead to greater value of output than their incremental cost. The new applications can increase electricity use through substitution for other fuels, as in induction heating, or they can decrease electricity use through greater energy efficiency, as in the replacement of arc welding by electron beam welding.

Again, since 1973 several factors affecting electricity use have undergone noticeable changes. For orderly planning by many sectors of the economy, it is important to know whether these changes will modify long-term trends connecting electricity use and the economy. Is a different form for the relationship more appropriate by introducing new variables? Or is only some adjustment needed, large or small, in the numbers that connect the customary variables?

If we address these questions so as to permit informed judgments about past relationships and future prospects, we shall have gone as far as we can. The future values of the economic variables themselves as inputs to consumption models are largely unpredictable. To estimate them requires not only skill but also luck.

Understanding the relationships between electricity use and the economy, with regard to both consumption and productivity, is important in formulating public policy, in regulating the industry, and in managing individual firms.

When the existing system of supply and demand works well, producing acceptable economic and social benefits, there is little need for government intervention beyond the usual activities of the state and federal regulatory system. A sound system of monitoring and evaluation is all that is needed. The existing system may, on the other hand, not work well. For example, the economic costs to a region, or to the nation, of a shortfall of electric power may be out of proportion to the cost of adding capacity, even though an individual utility may find it financially inadvisable to build a new plant. Also, though consumption may be satisfied, or even reduced, under a current set of conditions, aggregate productivity benefits from increasing efficiency or adding capacity may exceed the costs of these steps. In this context, recall that because of regional variations in electricity production and use, the adequacy of supply may vary regionally in ways not reflected by aggregate national data. On the other hand, it may prove more economical to reduce electricity use or to slow its growth, by increasing the efficiency of its use and substituting other production factors, than to expand supply. In any case, public policies may help ameliorate problems in the system by means of legislation, regulatory changes, investment incentives, or stimulation of research.

With regard to regulation, better knowledge of the relationships between electricity use and the economy, concerning both aggregate and particular end uses, should facilitate better decisions on many issues: rate design, capital investment, required reserve capacity, fuel contracts, cost recovery rules, and admissible research costs.

With regard to individual firms, the decisions of utilities as well as their suppliers would of course benefit from a better grasp of the interactions at work. At stake for the utilities and, by extension, their investors, are the consequences of allocating funds among additional plants, load management equipment, and conservation measures. Suppliers must anticipate the kinds and amounts of plant equipment and fuels that utilities will need.

The Structure of the Task

The committee's task, stated more fully in Appendix A, was to look at the role of "electricity" in "economic growth." Both these terms are familiar but, as in using many terms, we should strive for precise definition and connotation.

Economic growth is conventionally measured by GNP. Electricity service is measured either by installed capacity to deliver power or by energy consumption. None of these measures expresses everything of importance for the relationships at issue, as is discussed further in Appendix B. Nevertheless, we concluded that these measures were generally those appropriate for our study because of the difficulty of establishing other adequate ones and the desirability of relating our own to previous work.

Another term used in the report is "electrification." Electrification means the adoption of processes and activities based on the use of electricity. The term connotes an application and associated equipment that use the special qualities of electricity, often for innovation. Electrification may increase or decrease electricity consumption, depending on such factors as whether there is a change from a nonelectrical to an electrical production technique, the amount of electricity consumed per unit of output, and the total units of output produced. The last can be substantially greater than before if product prices fall because of more efficient production.

The terms "productivity" and "productivity growth" are used in their usual economic senses. Productivity means output per unit of input, measured in appropriate units, whether for a single kind of input or for a combination of inputs. Productivity growth is the change in productivity from one point in time to another, usually expressed as a percentage. "Productivity growth rate" is productivity growth per unit of time.

Figure 1-1 illustrates the system that we examined. The complexity of the figure reflects that of the real situation and thus the complexity of any useful analysis. We sought to describe the relationships between the central elements in this diagram: electrification, productivity growth, GNP, and electricity consumption. We tried to summarize what is currently known about these relationships and to indicate some uncertainties. To do so we had to consider several additional factors. These factors include the prices of electricity and of substitute fuels and the costs of electrical and nonelectrical processes. We considered direct effects (for example, the price of electricity on electricity consumption) and also indirect effects (for example, the income effect of conservation and electrification, freeing resources for other uses). When possible we tried to quantify these relationships when referring to the past; we could discuss them only qualitatively when referring to the future.

The various chapters focus on different parts of Figure 1-1.

Chapter 2 discusses the historical relationship between electricity consumption and GNP. Electricity consumption is first analyzed as a function of GNP. Gross product originating (GPO) and disposable personal income (DPI) are then used as measures in a finer analysis to reflect economic activity in different sectors. The central subject of Chapter 2 is depicted in the right central part of Figure 1-1: the arrow between GNP and electricity consumption points to the right

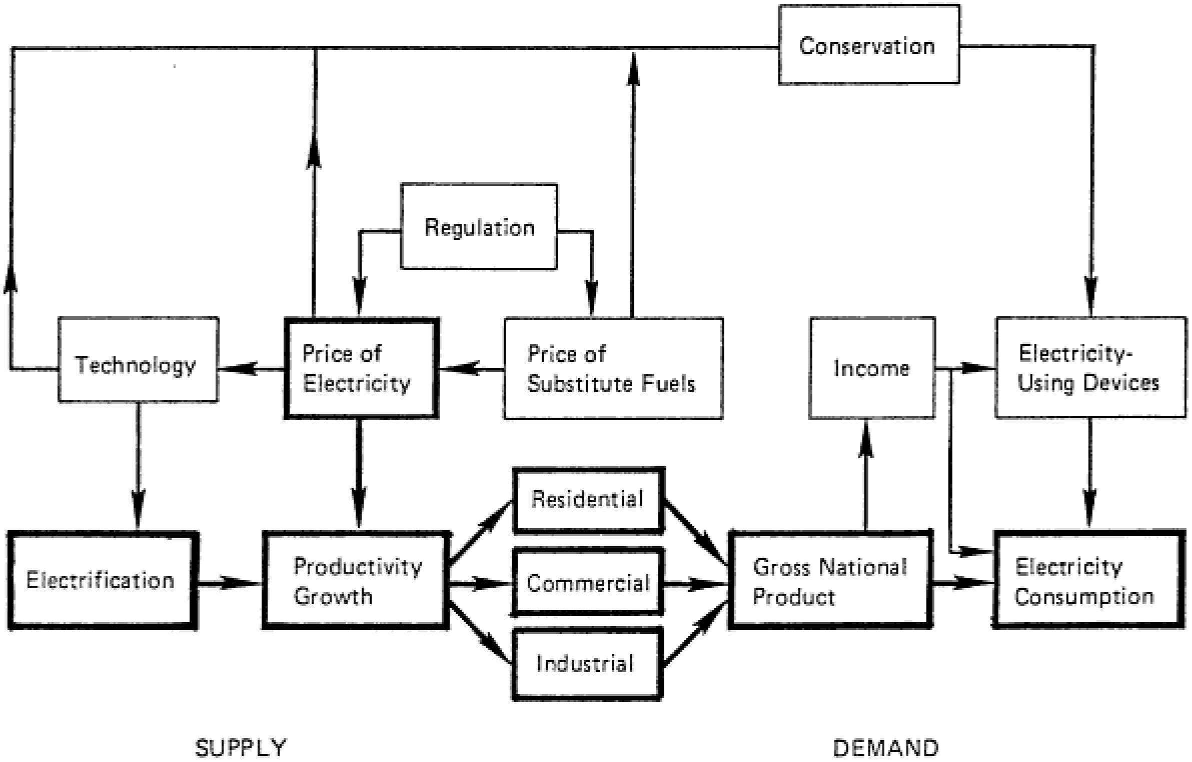

Figure 1-1
Relationships affecting electricity and economic growth.

because we consider how the level of economic activity affects electricity consumption. A later part of Chapter 2 discusses available evidence on how both the price of electricity and the price of nonelectric (substitute) fuels have affected electricity consumption. The influence of price links the left (or supply) side of the diagram with the right (or demand) side.

Chapter 3 looks at the role of electricity in productivity growth. Productivity growth is one of three inputs to economic growth, the others being capital and labor growth. This chapter finds that the electrification of productive processes, as one type of technical change, may have special effects on productivity growth. As is shown in Chapter 4, these effects are due to the flexibility and high quality of electricity as energy in application. Chapter 3 demonstrates that the prices of both electricity and other fuels, along with their technical characteristics, do influence productivity growth in most industries. The relationships among these variables are depicted in the left and central parts of Figure 1-1.

Chapter 4 looks at examples of the influence of electrification on economic activity, emphasizing further technical potentials. This chapter discusses the characteristics of various forms of electrification, their potential engineering and economic effects on general productive efficiency, and whether they may result in a net increase or decrease in electricity consumption per unit of output. This discussion is illustrated by some examples of technical change in different sectors of the economy. The examples show how electrification affects efficiency for the process and the firm and, by implication, how these gains can provide productivity growth in the aggregate. Chapter 4 is represented by the lower left corner of Figure 1-1.

In Chapter 5 we return to the subject of Chapter 2, but with attention to the future. Given the current uncertainty about whether the recent relationship between electricity use and GNP continues as before, we cannot foretell a precise future relationship between these variables. Furthermore, we are in no position to forecast the future growth rates of GNP and prices. Even so, we can consider the forces likely to influence the relationship between GNP and electricity use, for example, changes in the composition of national output, the prices of electricity and nonelectric fuels, and energy conservation. We also note that these forces have both direct and indirect influences. For instance, the individual consumer who realizes the benefits of conservation will enjoy greater disposable income. Similarly, if future electrification leads to greater overall productive efficiency and to lower electricity use per unit of output, this indirect effect on disposable income should lead to greater expenditures on goods and services. In turn, this would increase electricity demand according to the strong correlation that has held between GNP growth and the growth in electricity use. Thus, Chapter 5 addresses the possible future relationships among most of the elements of our diagram, but in a qualitative way.

These chapters together provide the information and analysis on which we based our conclusions. For the reader's convenience, our principal conclusions, along with statements of our rationale, appear below, and then our recommendations, which flow from these conclusions.

CONCLUSIONS

Electricity Consumption

Electricity use and gross national product have been, and probably will continue to be, strongly correlated.

Numerous representations of the relationships between economic activity and electricity use are possible.* We considered a number of these representations and discuss some in the report. The relationship we emphasize is based on considerations of simplicity and of adequacy in satisfying the committee's task. This relationship is at a high level of aggregation (between total electricity use and GNP) and takes a simple functional form (linear) such that one principal variable, GNP, is capable of explaining much of the variation in the other, electricity use, as they both change with the passage of time.

In this century, the electricity use-economic activity relationship has been characterized by four well-defined periods. Within each period, the relationship has been linear and stable. The first period was prior to World War I and the second from the end of World War I through the 1920s. In the third period, from 1930 through the end of World World II, the linear relationship paralleled that of the 1920s. The fourth period began after World War II and may still be continuing, although the relationship holding after the 1973 Arab oil embargo is still in dispute. We cannot tell conclusively whether the relationship after 1973 simply reflects variations from the most recent trend line, such as have occurred before, or whether a fundamental change in the relationship is taking place.

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* The possibilities encompass various aggregations of data (by nation, sector, region, or household), various functional forms of the relationship (linear or another form of growth curve), the addition of potentially relevant variables (population and household data, prices, inventories of electricity-using equipment, labor force data, and time), and various transformations of variables from their "natural" units (for example, kilowatt hours and dollars) to other forms, such as annual percentage increases. What we know does not allow us to disentangle the individual roles of all the possibly relevant variables in the electricity-economic activity relationship. Moreover, obviously no one formulation is best for all purposes. For example, a linear formulation may best illustrate the long-term historical record, while certain logarithmic representations may best serve more specific analytical needs.

Historic trends in the electricity use-GNP relationship include the effects of a host of factors not explicitly identified in the linear equation representing it. Among those believed important are the prices of electricity and competing energy forms, the composition of national output, regional economic activity, technical change, conservation practices, and government policies. Only when there are major perturbations in the trends (not simply movements about the trend lines) of these underlying variables would changes in the basic electricity use-GNP relationship be expected. Even then, some effects may cancel each other (such as rises in both electricity and other energy prices). Lesser variations in these underlying variables produce temporary deviations from the electricity use-GNP relationship. Two forces believed capable of altering the trends of future electricity use-economic activity relationships are electrification and conservation. However, their potential effects, like those of the other underlying variables, are not readily quantified.

Electricity and nonelectrical energy prices are generally acknowledged as factors determining electricity consumption. However, by far the most important contribution to explaining consumption in the past has been GNP. The observed departure on occasion of electricity consumption from the main trend line may be explained in part by taking price changes into account. Furthermore, there is an implicit dependence of electricity consumption on energy prices through the dependence of GNP in part on productivity growth, which in turn is shown to depend partly on energy prices.

Productivity Growth

> Productivity growth may be ascribed partly to technical change; in many industries technical change also tends to increase the relative share of electricity in the value of output, and in these industries productivity growth is found to be the greater the lower the real price of electricity, and vice versa.

Economic growth, or percentage change in GNP, results from growth in three factors: capital input, labor input, and productivity. Productivity accounts for increases in output in excess of the contribution of the first two factors. Productivity growth for the economy as a whole derives mainly from sectoral productivity growth and any reallocations of value added, capital input, and labor input among the sectors of the economy.

The decline in the rate of U.S. economic growth since the early 1970s is associated with a decline in sectoral productivity growth rates rather than a reduction in the aggregate growth rate of capital and labor inputs or the reallocation of value added, capital input, or labor input among sectors. Chapter 3 shows that this sectoral decline in productivity growth is strongly associated with an increase in energy prices.

Sectoral productivity growth may be modeled as a function of the relative prices of major inputs—capital, labor, electricity, nonelectric energy, and materials—and the level of technology. One comprehensive model of this sort shows that technical change and reduced electricity prices have a related effect on many industries. First, for these industries technical change is electricity using; that is, it is found to increase the contribution, relative to those of other inputs to production, that a given change in electricity input value makes to change in output value and so tends to increase the relative share of electricity in the value of output. Second, for the same industries the productivity growth arising from the technical change increases as electricity prices decrease, and conversely.

Such effects are found for nonelectrical energy in even more industries.

The decline in the real cost of electricity, which resulted in part from dramatic increases in the thermal efficiency of electric generation, increased electricity use and stimulated productivity growth until the early 1970s. The reversal in the decline of electricity costs, combined with a rise in the prices of primary fuels after the international oil price increases of 1973 and 1979, has permanently reduced productivity in many industries from what it would otherwise have been. This result may be explained partly by the substitution of less efficient inputs for these energy inputs.

Technical Change

Technical change has made possible many new opportunities for exploiting the special qualities of electricity. In the past these changes were often associated with increased intensity of electricity use, but in the future their net effect on that intensity will depend on the balance between their increased penetration and the increased efficiency of these applications.

Once generated, electricity has unique properties that make it an attractive form of energy. These properties include a highly ordered form (including the ability to be focused for efficient use and to produce very high temperatures), flexibility, and cleanliness of use. There is substantial potential in the major consuming sectors for further applications of electrical energy that take advantage of these special properties. We call such innovations electrification.

There are several different forms of electrification: (1) changing either old or new processes so that they rely on electricity rather than on fossil fuels, or direct wind or water as a source of mechanical energy, or human labor—changes generally associated with an increase in the intensity of electricity use; (2) converting older electrotechnologies (such as motor drive in manufacturing) to advanced ones to meet end-use requirements better —changes that often increase economic efficiency and may either increase or decrease the intensity of electricity use; and (3) the rapid penetration of new activities that depend on electricity, such as the growth in the use of computerized techniques—changes that may either increase or decrease the intensity of electricity use.

Some kinds of electrification increase electricity intensity (electricity use per unit of economic output) through wider application of electrical processes. Some kinds decrease electricity intensity through productivity gains. In the aggregate it is found that the increase in electricity intensity with GNP is relatively small because the two effects tend to be offsetting.

Electrification can change not only the form of energy used but also the share and absolute quantity of other inputs, including labor, capital, and materials. In addition product quality and even manufacturing location can be affected. Technical change in the form of electrification has historically contributed to increased productivity and thereby to increases in GNP. We can expect this trend to continue.

The Effects of Price Changes

> Electricity prices and alternative fuel prices affect electricity consumption in two ways: first, they directly affect the use of electricity and nonelectric fuels as input factors of production; second, they indirectly affect productivity growth and thereby economic growth.

If electricity prices alone rise (for example, because of a rise in plant and equipment prices), electricity use will decrease in accordance with elasticity of demand with respect to its own price. This result will occur through improving the efficiency of electricity use and through substituting other inputs for electricity.

A rise in the price of those fuels that compete with electricity, without a corresponding increase in the price of electricity, will increase electricity consumption because of elasticity of demand with respect to the prices of other fuels.

If electricity prices rise because of a rise in primary fuel prices, a reduction in electricity use through its own-price elasticity will occur and be offset to some degree by an increase in the use of electricity as a substitute for primary fuels, that is, through cross-price elasticity. The numerical values of these elasticities have not been well established, but current estimates of price elasticities suggest that the two effects may cancel each other.

Any increase in the real price of electricity will indirectly further decrease electricity use because it will lower productivity growth rates in many industries, in turn leading to a lower rate of economic growth.

Reductions in electricity prices yield an opposite set of results, as indicated historically.

Conservation

> There is further potential for increasing the efficiency of electricity use, particularly in the residential and commercial sectors.

Promising technologies have been identified for increasing the efficiency of electricity use. Their greatest promise is in the residential and commercial sectors, where there has been less investment in efficiency improvements than in the industrial sector since the Arab oil embargo. Energy price increases provide incentive for investments in conservation. The main constraints to such investment have been immaturity of the technologies, lack of information, lack of capitalization funds, inefficient electricity and fuel pricing, and doubts about the cost-effectiveness of such investment.

Of particular interest for the residential and commercial sectors are potential improvements in building envelopes and lighting systems, which can be incorporated in new construction and retrofitted to existing buildings. Although these improvements may themselves reduce the intensity of electricity use, there may be other factors, hard to predict, that increase electricity consumption through new uses of electricity in production and household applications. In addition, many established uses of electricity, such as for air conditioning and electric space heating, still show potential market growth.

The effects of residential conservation investments do not show up directly in sectoral productivity measures. However, their macroeconomic effect may be evidenced in a change in the composition of sectoral output and in changes in consumption from the income effect of reduced energy costs. In the commercial and industrial sectors those conservation measures that are cost-effective would appear in measures of sectoral productivity growth.

Evidence of success in conservation and load management is provided by programs implemented by electric and gas utilities. Conservation and load management, if cost-effective, can also benefit economic growth by reducing the costs of electricity supply, and thus the price of electricity, through improving the efficiency of existing and new generating facilities in producing given levels of electric energy.

The Composition of National Output

> Changes in the composition of national output toward less electricity-intensive goods and services have been offset by growth in the intensity of electricity use within all the major use sectors so that the combined effect on electricity demand growth has not yet been great. However, if the trend toward a leveling off in sectoral electricity; intensity growth that began in the late 1970s continues, future shifts toward less electricity-intensive goods and services are likely to dampen electricity demand growth relative to national output.

Looking at the sectoral composition of national output is one means of analyzing structural changes in the economy. Gross product originating (GPO) in producing sectors is often used to measure and compare their output. Employment figures are also widely used, but they are not as useful as GPO in analyzing the relationships of electricity use to other factors since they account for only one of the inputs to sectoral output.

Since 1950 the share of GPO in the commercial sector has increased steadily, while that in the industrial sector as a whole has declined. This decline is almost entirely due to a decrease in the relative importance of agriculture, mining, and construction as components of the industrial sector. The share of manufacturing GPO remained fairly constant over the entire postwar period, although within manufacturing there has been a shift toward less electricity-intensive industries.

The electricity intensity of the industrial sector is about three times that of the commercial sector, so that shifts away from industry, all other things being equal, would lead to a decline in electricity intensity for the total economy. However, there were large increases in average electricity intensity in all three of the major consuming sectors after World War II, which more than counteracted the negative influence on overall electricity intensity of the shift from industrial to commercial output. Almost all the growth in average sectoral electricity intensity occurred prior to 1973; by 1983 industrial and commercial sector electricity intensities were back near their 1973 values, while residential electricity intensity remained stable from about 1977. It is uncertain whether recent declines in sectoral electricity intensity growth represent the beginning of a new long-term trend or a response to short-term influences.

Regional Differences

> Valid conclusions about electricity demand drawn from national data do not necessarily pertain to regional circumstances; there are significant regional differences in such factors as economic output, prices, electricity supply mix, availability of generating capacity, climate, and regulatory environment.

With regard to economic activity, the regional factors important to electricity consumption include overall level of output, industry mix, labor and resource availability, and the relative importance of a region's commercial and industrial sectors. With regard to energy use, important regional factors include electricity and nonelectric energy prices, electricity supply mix, climate, and regulation. Shifts in demographic characteristics and regional activity may alter national electricity use patterns, although probably gradually and in a small way. National policy decisions should be sensitive to important regional differences.

RECOMMENDATIONS

The principal focus of this study is a better understanding of the complex relationships between electricity use and economic growth. Two important conclusions underlie the recommendations that follow. First, there has been a strong correlation between the use of electricity and the magnitude of GNP. Second, the recent research described in Chapter 3 was judged sufficiently significant to put forward with some confidence its thesis that there is a strong connection between electricity and productivity growth.

> 1. The relationship between electricity and productivity is so important that it should be considered in developing federal and state energy and economic policies.

Productivity growth is central to solving many problems facing the United States, ranging from the federal deficit to the balance of trade. Consequently, all possibilities of stimulating productivity growth, including attention to electricity supply and use, should be evaluated and pursued in accord with their promise.

* * * * *

> 2. To foster increased productivity, policy should stimulate increased efficiency of electricity use, promote the implementation of electrotechnologies when they are economically justified, and seek to lower the real costs of electricity supply by removing any regulatory impediments and developing promising technologies to provide electricity.

The findings of this report establish a connection between electricity and productivity growth. The two factors that must coexist to realize the productivity growth associated with electricity are technical change and favorable electricity supply conditions. In addition, cost-effective increases in the efficiency of electricity use will themselves not only increase productive output for a given input of electricity but also free income for other purposes. These points suggest that federal and state policies that promote lowering the real costs of electricity supply and use, through research and development or through more efficient pricing by regulatory authorities, will benefit productivity growth.

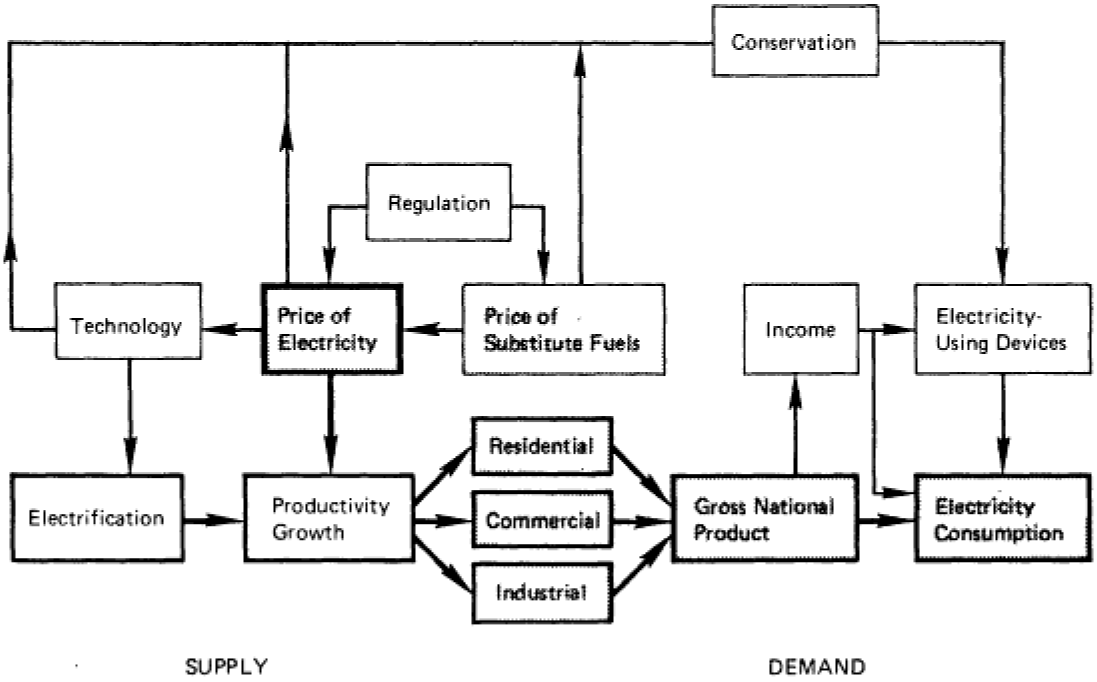
* * * * *

> 3. Further research should be undertaken to identify and quantify the forces affecting the relationships between electricity and economic growth in view of their critical importance, complexity, and regional diversity.

The strong and persistent relationship between electricity use and GNP requires that close attention be paid to the adequacy of electricity supply to sustain a high future rate of economic growth. The adequacy of electricity supply can be maintained not only through new generation facilities but also through efficiency improvements that use existing generating capacity better. Although favorable electricity supply conditions of themselves will not assure economic growth, a lack of adequate supply would almost certainly constitute a serious impediment to such growth. In making this point we are keenly aware of the need to learn more about the correlations and the causal relationships between economic growth and electricity use. As pointed out above, well directed policy, regulation, and management decisions rest on such knowledge. It should be systematically sought and better established. Otherwise progress toward greater economic efficiency, innovation, and competition may suffer.

2

Historical Perspective



This chapter provides a historical perspective on the relationship of electricity to economic growth. It deals with the shaded portions of the above reproduction of Figure 1.1. Early patterns are briefly noted. A more extended discussion of the period after World War II goes into the correlation of electricity use with gross national product (GNP), patterns of sectoral electricity use, changes in composition of economic output, and the effects of price changes. This material forms the basis for comment on the likely continuity of prior relationships and possible changes in them. The chapter, in conjunction with further discussion in Chapter 5, helps to support two of the principal conclusions that the study draws:

- Electricity use and gross national product have been, and probably will continue to be, strongly correlated.
- Changes in the composition of national output toward less electricity-intensive goods and services have been offset by growth in the intensity of electricity use within all the major use sectors so that the combined effect on electricity demand growth has not yet been great. However, if the trend toward a leveling off in sectoral electricity intensity growth that began in the late 1970s continues, future shifts toward less electricity-intensive goods and services are likely to dampen electricity demand growth relative to national output.

HISTORICAL PATTERNS: 1902 TO 1983

The Growth of Electricity and Other Energy Consumption

Electricity is such a versatile energy form that its use and the number of its applications have grown rapidly throughout the twentieth century. Electricity consumption continues to grow more rapidly than that of other energy forms. As a consequence, the proportion of the nation's primary energy supply used to produce electricity has expanded substantially—from near zero at the turn of the century to 36 percent in 1983. The growing importance of electricity as a component of total energy supply can be seen in Figure 2-1, which shows the growth in primary energy input, in British thermal units (Btu), for the production of electricity.

Another way of measuring the comparative growth of electrical and nonelectrical energy is by directly comparing the energy delivered by electricity (instead of by the primary energy consumed in its generation) and the energy delivered by other forms (mostly coal and coke, oil products, and natural gas). The average annual growth rates shown in Table 2-1 are based on such data. Clearly electricity consumption has grown at a higher rate than has the consumption of other energy forms throughout the twentieth century, including the most recent decade. In fact, over the last decade electricity use continued to grow, while that of all other energy declined (an unprecedented occurrence in the long historical record). Nevertheless, the rate of growth of electricity consumption itself fell sharply during the recent past compared with its growth rates in all earlier periods.

That the rate of growth of electricity use has tended to decline, particularly compared with the early periods of its introduction, is not surprising. As the base from which growth is measured becomes larger, even ever-growing absolute increments can translate into smaller percentage growth rates. By the same token, the early rates of

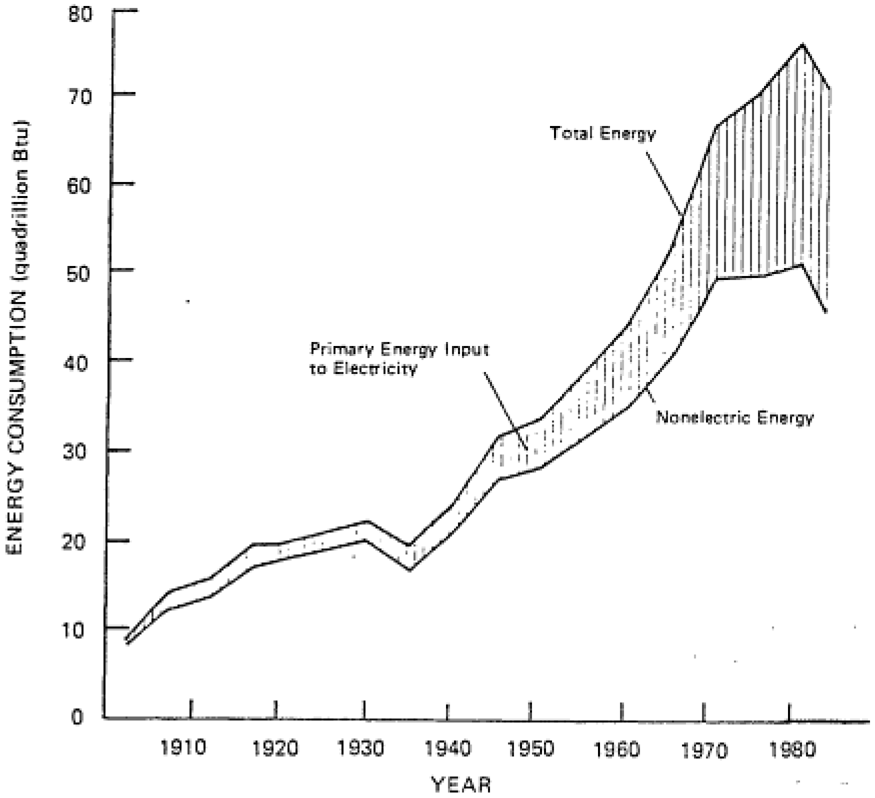


Figure 2-1
Historical trends in U.S. energy consumption, 1902 through 1983.
Source: U.S. Bureau of Mines, as presented in Towards Project Independence: Energy in the Coming Decade, prepared for the Joint Committee on Atomic Energy, U.S. Congress, 94th Congress, 1st Session (December 1975); Edison Electric Institute, Historical Statistics of the Electric Utility Industry through 1970, and Statistical Yearbooks; U.S. Department of Energy, Annual Energy Review, various issues.

TABLE 2-1 Average Annual Growth Rates in Total Energy, Electricity, and Nonelectric Energy Consumption for Selected Periods, 1902 through 1983 (Percent per Year)

Period	Total Energy	Electricity	Nonelectric Energy
1902-1912	6.1	15.5	5.6
1912-1920[a]	2.9	10.8	3.3
1920-1930[a]	1.2	7.3	1.3
1930-1940	0.7	4.6	0.5
1940-1950	3.5	7.9	3.0
1950-1960	2.8	8.1	2.2
1960-1973	4.1	6.7	3.4
1973-1983	-0.5	2.0	-1.7

[a] Average annual growth rates for total energy and for nonelectric energy were computed from British thermal units (Btu) of consumption. The growth rate for electricity was computed from kilowatt hour figures. Because of rapidly improving efficiency of electric power generation in the early years, electricity kilowatt hours grew much faster than Btu input for electricity generation. This aspect of the computation is the reason that, for these two periods, the growth rate of total energy appears to be lower than the growth rate of both of its components.

SOURCES: U.S. Bureau of Mines, as presented in Towards Project Independence: Energy in the Coming Decade, prepared for the Joint Committee on Atomic Energy, U.S. Congress, 94th Congress, 1st Session (December 1975); Edison Electric Institute, Historical Statistics of the Electric Utility Industry through 1970, and Statistical Yearbooks; U.S. Department of Energy, Annual Energy Review, various issues.

growth of a newly emerging product or industry, such as electricity in the first part of this century, will loom large compared to those of already established quantities, such as population, GNP, or the use of other energy forms.

In considering electricity growth in historical perspective, it is instructive to review time trends, as such, and to compare the growth rates of electricity with those of other energy forms. However, the focus of this study is electricity in economic growth. Accordingly, our goals are to try to discern trends in the relationship between electricity and economic growth and to consider some of the factors underlying these trends.

Electricity Growth in Relation to the Growth of Gross National Product

How should the relationship between electricity use and economic growth be expressed? Our approach is to look first at the relationship in aggregate terms, that is, in terms of total electricity made available in the United States, regardless of source, and of GNP, expressed in constant dollars. Later this relationship will also be examined, although only for the years following World War II, in terms of the major sectors of electricity use: residential, commercial, and industrial. The discussion addresses the nature of the aggregative relationship, changes in this relationship over time, and sectoral relationships compared to the aggregative, or national, one. It is well known that regional disaggregations will exhibit diversity, but this chapter does not address that effect.

When standard statistical techniques are used to measure the relationship between annual levels of electricity use and GNP (in constant dollars), certain regular features of the historical record appear. Perhaps the most significant characteristic of the relationship is its stability over appreciable segments of time. This stability is indicated in Figure 2-2 (with additional detail in Figure 2-3), which displays lines of regression for four periods covering most of the twentieth century to date.* For any point on these lines one may calculate an average electricity intensity, that is, electricity consumption per unit of GNP. Changes along these lines relate increments in electricity use to increments in GNP; each period is marked by a stable linear relationship, which, though showing some annual fluctuations, indicates a strong tendency toward a constant incremental intensity of electricity use within each period.

Equally significant is the fact that there are only a few changes in the slope (and the level) of the regression line over the long historical record. Clearly discernible changes in slope occurred following World Wars I and II. Even the Great Depression did not result in a change in slope; the level of the regression line did shift upward, however, reflecting the fact that during this period GNP

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* A regression is the best functional relationship between two (or more) correlated variables as judged by a particular statistical criterion, such as the criterion of ordinary least squares.

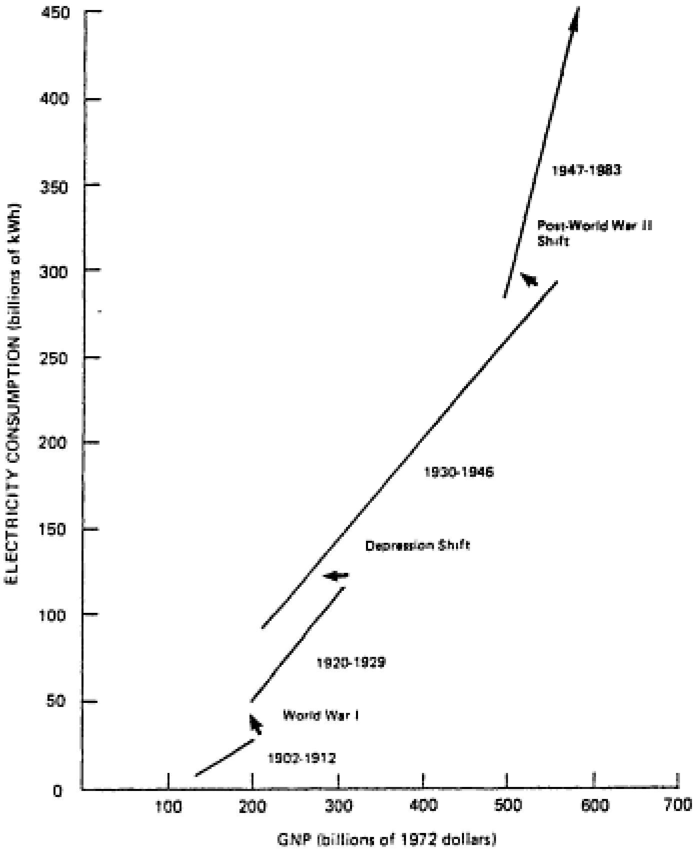

Figure 2-2
Electricity consumption vs GNP in the United States, with lines of regression by periods, 1902 through 1983.
Note: GNP is expressed in constant (1972) dollars. Data for 1902 through 1928 have been converted from constant (1958) dollars in U.S. Department of Commerce, Bureau of the Census, Historical Statistics of the United States, Colonial Times to 1970, Bicentennial Edition, Part 2, Series F1-5, p. 224; for 1929 through 1980 from Council of Economic Advisers, Economic Report of the President, February 1984, p. 222; for 1981 through 1983 from Council of Economic Advisers for the Joint Economic Committee, Economic Indicators, March 1985, p. 2. Electricity consumption is expressed as "electricity made available in the United States." Conceptually this quantity includes utility generation and nonutility generation (industrial self- and co-generation), and net imports. Electricity data sources are Edison Electric Institute (1973, 1984a).
Source: Compilation and figure by Energy Study Center, Electric Power Research Institute, Palo Alto, California.

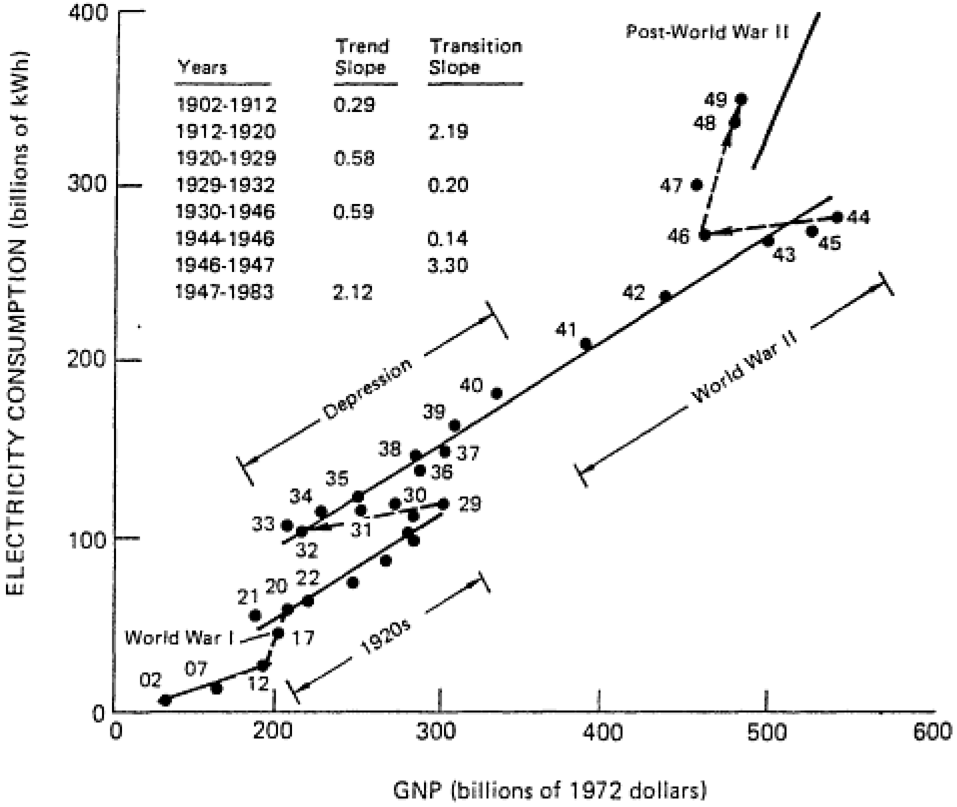

Figure 2-3

Electricity use and GNP—the transitions.

Note: GNP is expressed in constant (1972) dollars. Data for 1902 through 1928 have been converted from constant (1958) dollars in U.S. Department of Commerce, Bureau of the Census, Historical Statistics of the United States, Colonial Times to 1970, Bicentennial Edition, Part 2, Series F1-5, p. 224; for 1929 through 1949 from Council of Economic Advisers, Economic Report of the President, February 1984, p. 222. Electricity consumption is expressed as "electricity made available in the United States." This quantity includes utility generation and nonutility generation (industrial self- and co-generation), and net imports. Electricity data sources are Edison Electric Institute (1973, 1984a) .

Source: Compilation and figure by Energy Study Center, Electric Power Research Institute, Palo Alto, California.

decreased relatively more than did electricity use. The record of the past decade poses the question of whether we are once again witnessing a change in slope, an issue that is addressed later in this chapter.

The specific findings embodied in Figures 2-2 and 2-3 may be summarized as follows:

1. From 1902 to 1912, (a period during which data on electricity use are available only for every fifth year), the national economy tended to use an additional 0.29 kilowatt hours (kWh) per additional dollar of GNP, measured in constant (1972) dollars.*
2. A transition to a new slope occurred between 1912 and 1920; the 1917 observation shown on Figure 2-3 appears to be transitional.
3. Between 1920 and 1929 the incremental use of electricity per unit of GNP averaged 0.58 kWh per dollar, twice the value that prevailed between 1902 and 1912.
4. Following 1929, GNP dropped by almost one-third, while electricity use declined only slightly. Consequently, average electricity intensity increased. However, the slope of the line for the years 1930 through 1946 did not change significantly from that for the years 1920 through 1929. Thus, incremental intensity of electricity use remained the same, even though average electricity intensity rose.
5. Another transition occurred following World War II, and the new trend line has persisted ever since (with a critical question remaining about the most recent past). The new slope shows on the average an increment of 2.12 kWh per additional constant (1972) dollar of GNP, about three and one-half times that characterizing the relationship observed between 1920 and 1946.

POST-WORLD WAR II TRENDS: 1947 TO 1983

The Growth of Electricity Use and of Gross National Product

The relationship between increases in electricity use and increases in GNP is shown for the full post-World War II period in Figure 2-4. The relationship appears to have persisted through the entire period, with the possible exception of a break since the mid-1970s. Although observations for the most recent years fall below the trend line, this fact is still consistent with a characteristic feature of the relationship, that is, a tendency for individual years to exhibit a cyclical pattern around the long-term trend line, as the figure shows.

However, to conclude that the data points after the mid-1970s are nothing more than a manifestation of a persistent cyclic pattern is only one way of interpreting the record for recent years. There has been a strong decreasing trend in the ratio of the annual percentage

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* A discussion of measures of electricity use and load demand, in terms of energy (kilowatt hours) and power (kilowatts), appears in Appendix B.

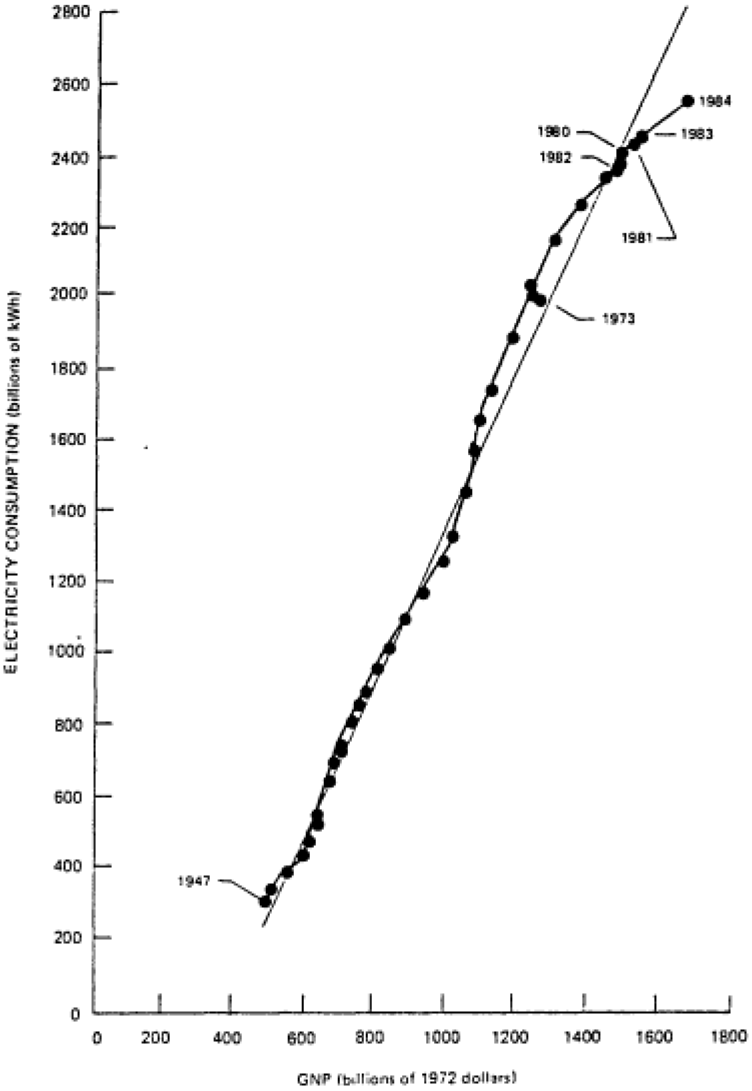

Figure 2-4

Electricity consumption vs GNP in the United States, 1947 through 1984.

Note: GNP is expressed in constant (1972) dollars. Data from Council of Economic Advisers, Economic Report of the President, February 1984, p. 222; Council of Economic Advisers for the Joint Economic Committee, Economic Indicators, March 1985, p. 2. Electricity consumption is expressed as "electricity made available in the United States." This quantity includes utility generation and non-utility generation (industrial self- and co-generation), and net imports. Electricity data sources are Edison Electric Institute (1973, 1984a).

Source: Compilation and figure by Energy Study Center, Electric Power Research Institute, Palo Alto, California.

growth of electricity use to that of GNP, and this fact is frequently cited as evidence that the relationship between the two has changed.

Figure 2-5 shows that the ratio of percentage electricity growth to percentage GNP growth has fallen from an average of about 2 before 1973 to about 1 today. This tendency toward convergence is consistent with the postwar linear relationship between the two variables. The electricity use-GNP line of regression for 1947 to 1983 shows an increment of 2.12 kWh of electricity for every constant (1972) dollar increment of GNP. In the early postwar period, when average electricity intensity was comparatively low (about 0.6 to 0.8 kWh per dollar), the high incremental electricity intensity (2.12 kWh per dollar) led to much higher electricity growth rates than GNP growth rates. As average electricity intensity has increased—to 1.57 kWh per constant (1972) dollar in 1983—the effect of the incremental electricity intensity (2.12 kWh per dollar) has relatively decreased, leading toward a convergence in growth rates.*

A critical question before us, then, is whether the long-standing post-World War II trend has been broken by another of the historically infrequent transitions, but for the first time toward a decline in the incremental intensity of electricity use. To shed more light on this question, we next examine some of the underlying forces that determine electricity use in relation to national output. Such influences include the trends of electricity use in the major consuming sectors, the effects of changes in the composition of national output, and the effects of changes in energy prices.

Electricity Use in the Major Consuming Sectors

Electricity use is ordinarily classified by three major consuming categories:

- Residential, that is, private households
- Commercial, that is, nonindustrial business establishments
- Industrial, that is, agriculture, mining, construction, and manufacturing. **

Table 2-2 shows the changing importance of each sector as reflected by its percentage of total electricity consumption over the postwar period. The residential sector sharply increased its share of

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* In other words, because of the nonzero intercept in the relationship (which appears as the offset of the regression line from the origin in Figure 2-4), the percentage growths of electricity and GNP along the regression line are more nearly equal where both quantities are large, as in the later years, than where both quantities are small, as in earlier years.

** These definitions differ somewhat from the Edison Electric Institute (EEI) sector definitions. However, for our purposes, the differences are not great enough to warrant concern, and so we have used the EEI statistics, with no change, to fit our categories.

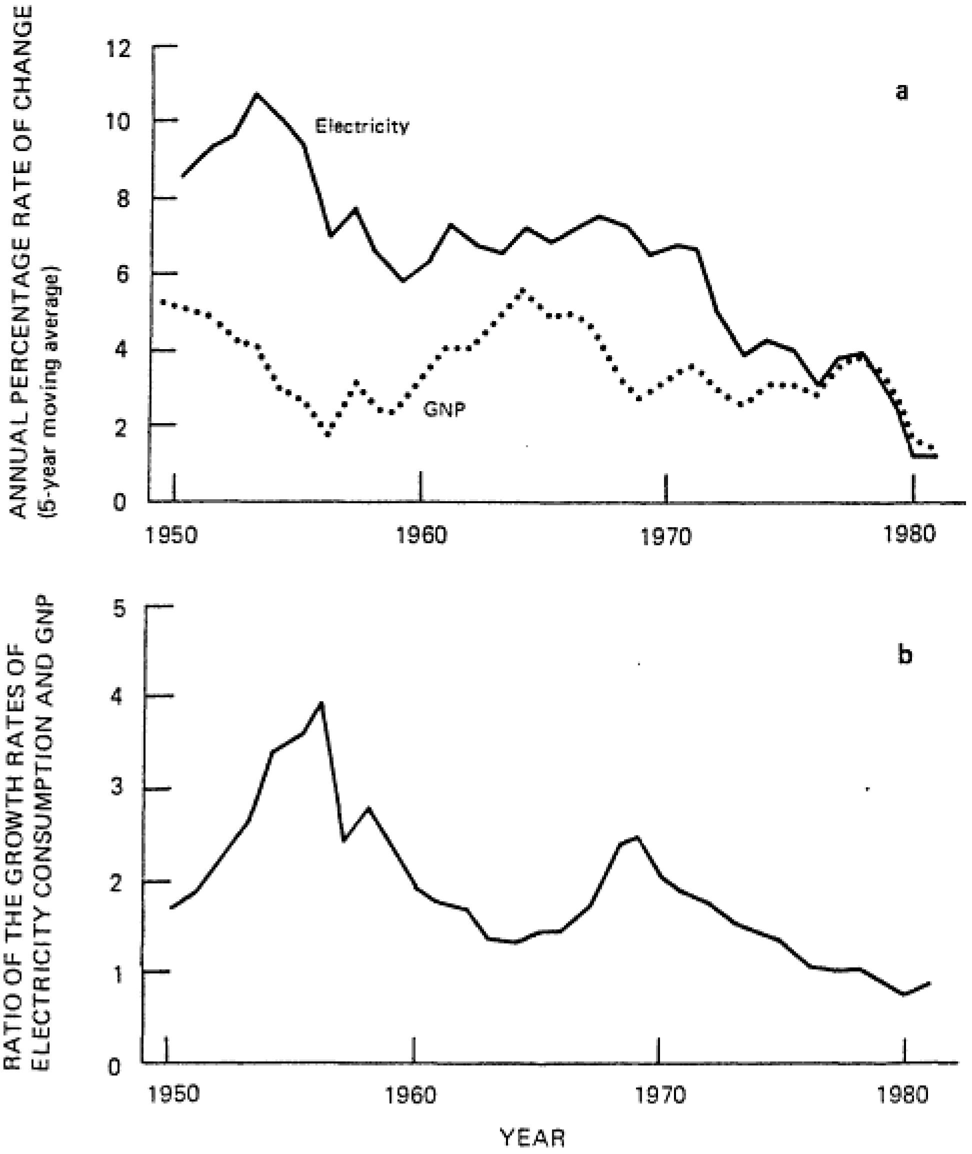

Figure 2-5
(a) Growth rates of U.S. electricity use and GNP, (b) ratio of the growth rates.
Source: Based on data from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, various issues; U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

TABLE 2-2 U.S. Electricity Sales by Sector (Percent of Total)[a]

Year	Residential	Commercial[b]	Industrial[c]
1950	20.6	20.1	59.3
1955	22.3	17.3	60.4
1960	25.4	18.4	56.2
1965	26.6	22.6	50.7
1970	29.9	24.7	45.4
1975	32.2	26.7	41.1
1980	33.5	27.2	39.3
1983	33.9	28.3	37.8

[a] Includes industrial self-generation.

[b] Small light and power, street and highway lighting, other public authorities, railroads and railways, and interdepartmental transfers.

[c] Large light and power and industrial self-generation.

SOURCES: Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, various issues.

electricity use from one-fifth to over one-third of the total. The commercial sector share increased sharply during the 1960s, and in 1983 it stood at 28 percent of the total. The industrial share, starting at 59 percent of the total, dropped dramatically after 1955, to 38 percent of the total by 1983.

These postwar trends in sectoral shares of electricity use parallel the underlying trends in the economic measures for each sector. That is, growth in disposable personal income (DPI), the residential sector surrogate for gross product originating (GPO) in the other two sectors, and commercial sector growth outpaced that of industrial output over the entire period.* In fact, if we examine the relationships between electricity use in these sectors and their respective economic measures, as in Figure 2-6, we find the same stable linear relationship (with cyclical variation) as is seen in the aggregate economy. Also, as in analyzing the aggregate case, one gains a different perspective when comparing the ratio of the percentage growth rates of electricity use and economic output measures. Figure 2-7 shows the same trend toward convergence between the sectoral percentage growth rates as was observed in the total economy. For further insight into these trends, we examine in more detail the postwar patterns of electricity use within each of the three sectors.

Trends in Residential Use of Electricity

The trend in residential electricity consumption since World War II falls into three distinct periods, corresponding roughly to the decades of the 1950s, 1960s, and 1970s, as shown in Figure 2-7. During the 1950s, the growth rate of electricity consumption was very high but steadily decreasing from about 14 to 8 percent per year. During the 1960s, this growth rate slowly accelerated to about 10 percent per year toward the end of the decade. It then dropped in the post-embargo period to an average of about 5 percent per year, until the late 1970s and early 1980s when it dropped further.

Figure 2-8 illustrates the changing pattern of residential electricity use in the first two decades after the war. In 1950 electricity went primarily to four end uses: lighting (29 percent), water heating (24 percent), refrigeration (17 percent), and cooking (11 percent). Between 1950 and 1960 electricity use per customer more than doubled. Over 50 percent of this increase is attributable to the three largest incremental end uses: refrigeration, water heating, and televisions. The introduction of frost-free refrigerators and the trend toward larger refrigeration units more than doubled the electricity consumption for this appliance by 1960. The penetration of electricity into the water-heating market doubled between 1950 and

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* GPO, the statistic used for both commercial and industrial outputs, is a measure of value added derived from the national income and product accounts; it emphasizes the sectoral origin of GNP.

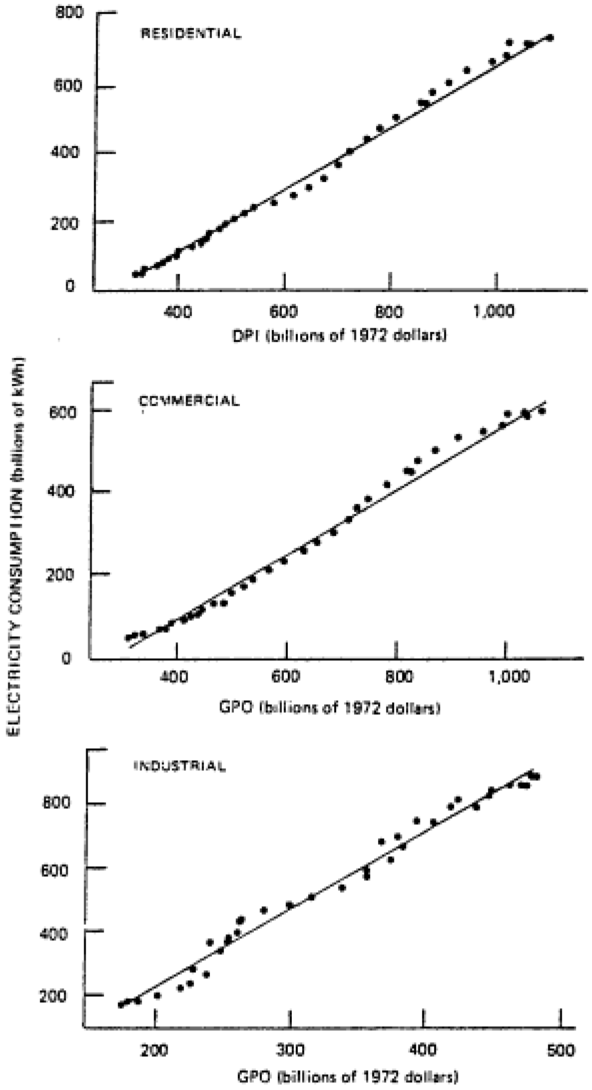


Figure 2-6

Electricity use-economic measure relationships, by economic sector, 1947 through 1983.

Note: Different scales are used for the three sectors to highlight the linearity of the electricity use-economic output relationship within sectors. Based on data from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, various issues; U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

Source: Compilation and figure by Energy Study Center, Electric Power Research Institute, Palo Alto, California.

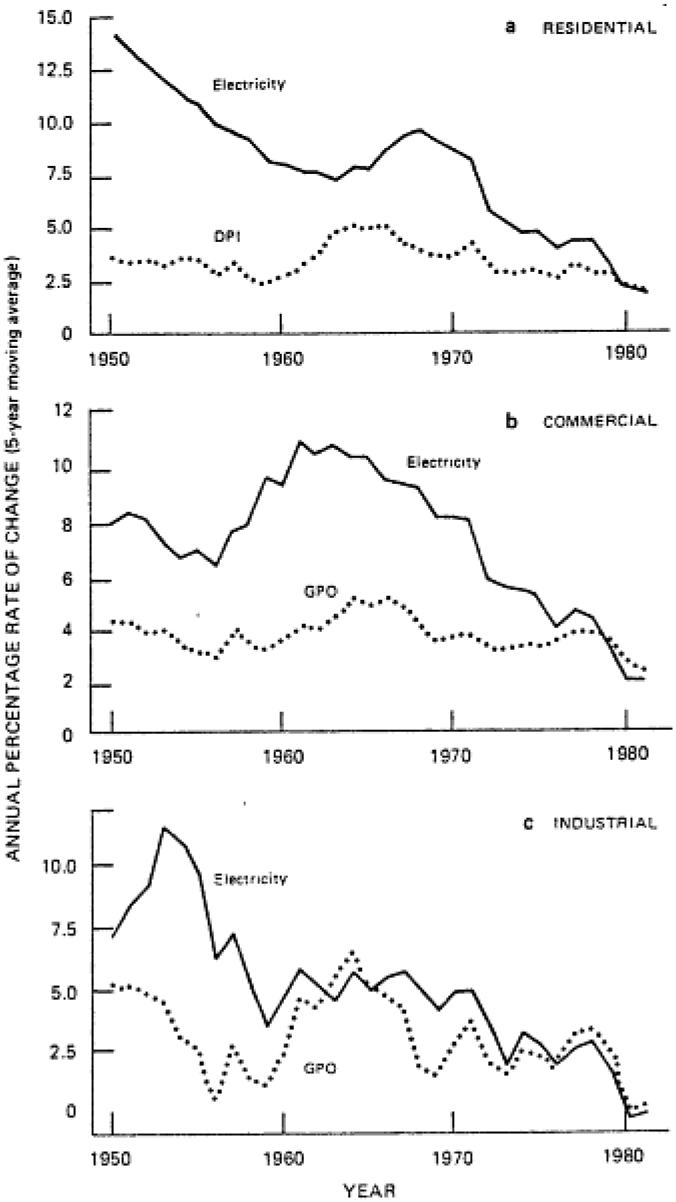
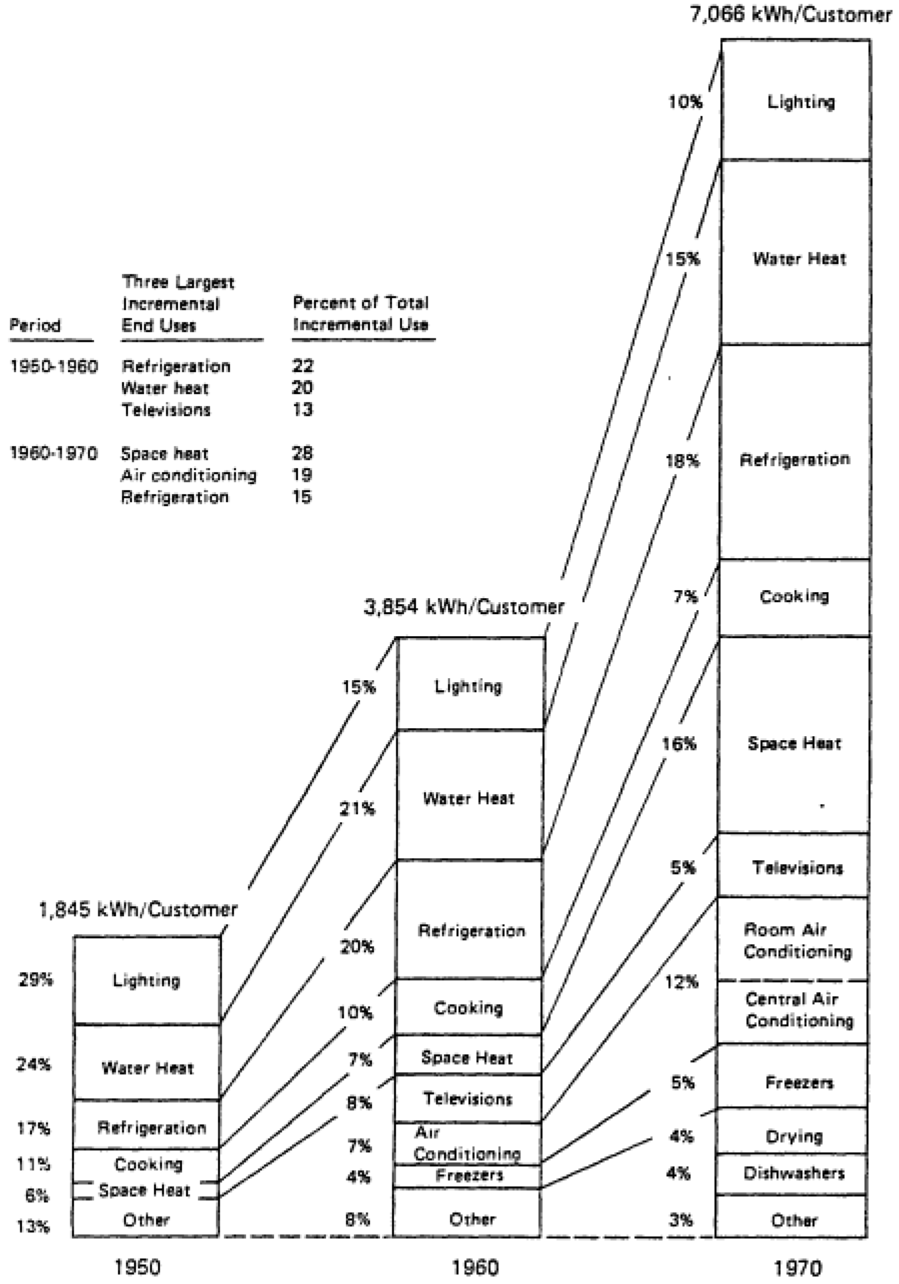


Figure 2-7
Growth rates of electricity sales and sectoral output indicators, 1947-1983: (a) residential, (b) commercial, (c) industrial.

Source: Based on data from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, various issues; U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.



Period	Three Largest Incremental End Uses	Percent of Total Incremental Use
1950-1960	Refrigeration	22
	Water heat	20
	Televisions	13
1960-1970	Space heat	28
	Air conditioning	19
	Refrigeration	15

Figure 2-8
Residential electricity use patterns, 1950, 1960, and 1970.
Source: Tansil and Moyers (1974).

1960, while the household saturation level for televisions increased from 13 percent in 1950 to 90 percent in 1960.

Electricity use per customer nearly doubled again between 1960 and 1970. However, as distinguished from the earlier decade, almost one-half of this increase is attributable to the increased penetration of electric space heating and air conditioning (from 2 to 8 percent and from 13 to 38 percent of all households, respectively). Both of these applications consume large amounts of electricity, so that even modest market penetrations can have a large influence on consumption levels. Refrigeration (accounting for 18 percent of electricity use in 1970) again accounted for a relatively large part of the absolute increase in electricity use as the trend toward using frost-free refrigerators continued. Moreover, in general, household appliances were becoming more electricity-intensive.

From 1970 to 1980 average consumption per household increased only 28 percent, as may be seen in Figure 2-9. One half of this increase occurred by 1973. Again the main contributors to incremental consumption were air conditioning, refrigeration, and space heating.

Within the residential sector electricity now accounts for about 58 percent of gross energy (28 percent of net energy) consumed.* More than half of this electricity is used in applications for which there is essentially no competition from other fuels, applications such as air conditioning, lighting, and most appliance operation.

Since 1980, electricity use per customer has decreased slightly. However, electricity continues to make significant inroads in space heating and air conditioning. While about 17 percent of the total occupied housing stock today uses electricity as its primary heating source, 50 percent of new single-family housing units (and a greater percentage of multifamily housing units) incorporate electric heating systems, up from 28 percent in 1970. Of all occupied housing units, 57 percent now have air-conditioning systems of some type, but only 27 percent are equipped with central air-conditioning systems. However, about two-thirds of new single-family homes are built with central air-conditioning systems, which indicates that such electricity penetration will continue (U.S. Bureau of the Census, 1984; U.S. Energy Information Administration, 1984).

Part of these trends can be attributed to the fact that much of the housing stock expansion is occurring in warmer climates, where electric heating and air conditioning are more prevalent. Almost three-fourths of all recent housing starts are in the southern and western regions of the country, although these regions accounted for only one-half of existing housing stock in 1973. However, both electric space heating and air conditioning are increasingly penetrating all regions of the United States (U.S. Bureau of the Census, 1984; U.S. Energy Information Administration, 1984).

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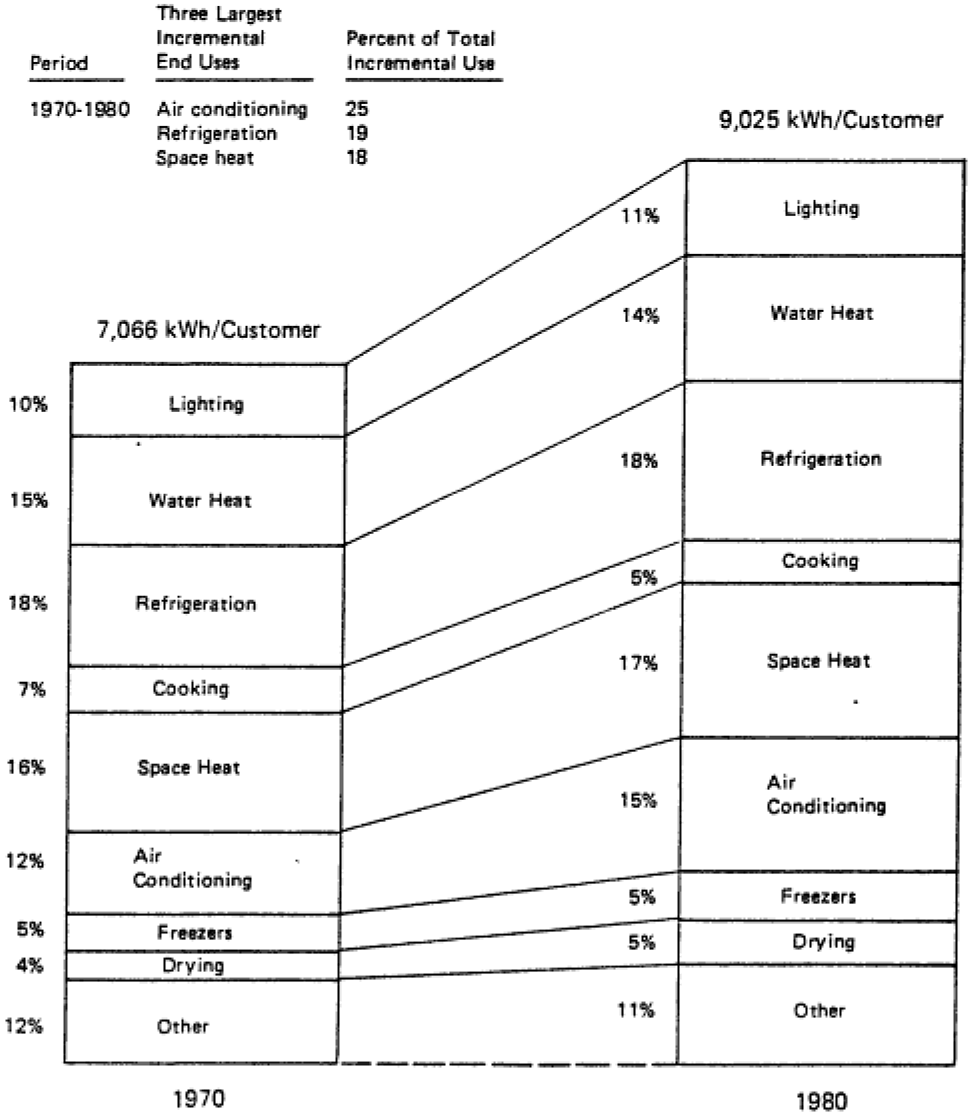
* Gross energy, which refers to primary energy input, includes the energy lost in generating, transmitting, and distributing electricity, whereas net energy does not.



Period	Three Largest Incremental End Uses	Percent of Total Incremental Use
1970-1980	Air conditioning	25
	Refrigeration	19
	Space heat	18

Figure 2-9
Residential electricity use patterns, 1970 and 1980.
Sources: Tansil and Moyers (1974); Geller (1983); U.S. Energy Information Administration (1982).

Given the increasing penetration of electric space heating and air conditioning, the slower growth in residential electricity use suggests that significant conservation measures are being used within this sector. Certainly, new housing is built to be more energy-efficient and many older houses are being retrofitted with energy-saving features. In addition, there is a trend toward manufacturing more energy-efficient appliances (Meyers and Schipper, 1984).

Trends in Commercial Use of Electricity

Electricity consumption in the commercial sector has grown faster than that in the other sectors since 1960 (Figure 2-7). The large increase in commercial electricity use between 1960 and 1973 (at a 9.5-percent average annual growth rate) has been attributed to increases in the use of mechanical air-conditioning systems and to new standards for building illumination, which resulted in increased lighting requirements (Solar Energy Research Institute, 1981). From 1973 to 1983, commercial electricity use continued to increase but at a much slower average rate of 3.1 percent per year. It appears that much of this increase was due to an increased penetration of electricity use in space heating. While it is estimated that about one-fourth of all commercial buildings are now heated with electricity, almost one-half of all commercial buildings constructed since 1973 use electric heat (Hirst et al., 1983).

Electricity represents 65 percent of gross energy (35 percent of net energy) consumed in the commercial sector, making this sector by far the most "electrified." More than one-third of commercial sector electricity is used for lighting, about one-third for air conditioning, one-fifth for space heating, and the remaining one-tenth or so for water heating and miscellaneous appliance operation (for example, cooking and refrigeration).

The declining growth of commercial sector electricity use during a period when output growth remained relatively strong points again to improvements in efficiency of use. New commercial buildings are generally constructed to be more energy-efficient than were older buildings (U.S. Energy Information Administration, 1984). Improved lighting systems and the introduction of computerized energy management systems will also increase the efficiency of energy use. On the other hand, the trend toward greater use of electric heating will probably continue; and the increased automation of office services will add to electrical loads, not only for equipment operation but also for waste heat removal.

Trends in Industrial Use of Electricity

Electricity use in the industrial sector grew at an average rate of 8 percent per year between 1950 and 1960. From 1960 to 1973, the growth rate of industrial electricity use averaged 4.7 percent per year before falling to an average of 0.6 percent per year from 1973 to 1983.*

Electricity represents 34.8 percent of the gross energy (13.5 percent of net energy) consumed in the industrial sector. Manufacturing accounts for 85 percent of total electricity use in this sector, with agriculture, mining, and construction activities accounting for the remainder.

In 1981, electricity represented about 46 percent of gross purchased energy (20 percent of net purchased energy) in manufacturing compared to 28 percent gross (10 percent net) in 1958. Manufacturing can be divided into two large groups: the process industries, in which the physical or chemical properties of materials are altered, and the nonprocess, or fabrication, industries. The latter group, which accounts for about 75 percent of manufacturing value added, is largely electrified already, with 57 percent of its combined gross energy requirements being satisfied by electricity. These industries require energy mainly for mechanical drive and low-temperature heating. The process industries, on the other hand, use much of their energy for high-temperature heating or steam raising, needs that historically have been satisfied by the use of fossil fuels. Electricity generally accounts for 25 to 30 percent of gross energy use in these industries. However, electrotechnologies are increasingly penetrating high-temperature materials processing, and they may make further inroads (Burwell, 1983). We will examine the manufacturing sector in greater detail below in considering structural economic changes.

Electricity use has continued to increase in agriculture and mining because of increased energy requirements for irrigation and mineral extraction. In agriculture, energy requirements for irrigation are increasing as groundwater supplies are being depleted and a greater percentage of water requirements must be satisfied by pumping from greater distances. In mining, depletion effects and environmental regulations have increased electricity requirements, mainly in oil and gas extraction and coal mining. Electricity use in construction is negligible (Werbos, 1984).

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* The electricity consumption of the federal government's gaseous diffusion plants for uranium enrichment represented about 20 percent of industrial sector demand growth in the 1950s, but has declined since then, except for a brief increase in the early and mid-1970s. Uranium enrichment operations are not expected to have an important effect on industrial electricity consumption in the near future. Excluding electricity consumption for uranium enrichment, the average annual growth rates of industrial sector electricity demand are 6.8 percent per year from 1950 to 1960, 5.5 percent per year from 1960 to 1973, and 0.7 percent per year from 1973 to 1983.

The Effects of Structural Change on Electricity Intensity

Measuring Structural Change

Structural change may be indicated by different economic indicators, such as the composition of GPO, employment, and final demand.

Table 2-3 shows that the share of GPO accounted for by industry fell from 38 percent in 1950 to about 31 percent in 1983. However, this change is accounted for almost wholly by declines in the relative importance of agriculture, mining, and construction. The manufacturing share of total domestic output has remained at about one-fourth during this entire period.

GPO in the commercial sector, a very broad classification that encompasses all output originating outside the industrial sector, grew from 62 to 69 percent. These figures encompass transportation; communications; electric, gas, and sanitary services; wholesale and retail trade; finance, insurance, and real estate; personal services; and government operations.

However, GPO composition is not the only way of looking at structural change. Another perspective is gained by looking at employment trends, shown in Table 2-4. As a share of total employment, industrial sector employment fell from about 45 percent in 1950 to about 29 percent in 1983. Commercial sector employment rose from 55 percent of total employment in 1950 to about 71 percent in 1983.

This information tells us that the commercial sector has been absorbing more of the growing labor force. This trend is especially true of part-time workers. On the other hand, the rapidly increasing share of commercial sector employment relative to output growth in that sector implies that growth of labor productivity (that is, output per unit of labor input) has been slower in this sector than in the industrial sector.

Still another way to view structural change is through the mix of final demand for goods, services, and structures, shown in Table 2-5. Since 1960, the share of goods in final demand has remained at about 45 percent, after dropping from 49 percent in 1950. Services have increased from about 39 to about 47 percent of final demand, while structures in 1983 accounted for 8 percent of final demand, down from 12 percent in 1950.

These data imply that the relative consumption of final goods has not changed much over the last 20 years. What has changed is the value composition of these goods, through various intermediate markups from such service activities as distribution and sales that have increased over time. Thus, compared to demand composition in 1950, a greater part of the final demand of goods now consists of value added in the services sector and a decreasing share is attributable to value added in industry.

TABLE 2-3 Gross Product Originating (GPO) in the U.S. Economy for Selected Years, 1950 to 1983 (Percent of Total)

Sector	1950	1960	1970	1983
Industrial	38.0	36.0	34.2	30.7
Agriculture	5.5	4.4	3.2	2.6
Mining	2.1	1.8	1.8	1.4
Construction	5.5	6.3	5.0	3.3
Manufacturing	24.8	23.5	24.3	23.4
Commercial	62.0	64.0	65.8	69.3

SOURCES: U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

TABLE 2-4 Employment in the U.S. Economy for Selected Years, 1950 to 1983 (Percent of Total)

Sector	1950	1960	1970	1983
Industrial	44.9	38.9	34.7	28.7
Agriculture	10.9	7.0	4.0	3.3
Mining	1.6	1.1	0.8	1.0
Construction	5.8	5.3	5.3	5.1
Manufacturing	26.5	25.4	24.6	19.3
Commercial	55.1	61.1	65.3	71.3

SOURCES: U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

TABLE 2-5 Gross National Product (GNP) by Major Type of Product for Selected Years, 1950 to 1983 (Percent of Total)

Product Type	1950	1960	1970	1983
Goods	48.9	45.5	44.9	44.9
Services	38.8	42.4	44.4	47.1
Structures	12.3	12.1	10.7	8.0

SOURCES: U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

Of the several ways of looking at structural change, the most significant for analyzing electricity use is the GPO (value-added) measure, since it provides a measure of total productive activity—embracing both labor and capital inputs—within any particular sector. GPO analysis shows manufacturing to have generally maintained its share of output over the postwar period. The shift in output has been from agriculture, mining, and construction toward selected commercial sector activities. The following two sections adopt GPO as the best measure of structural change.

Electricity Intensity of the Sectors

Electricity intensity is defined as total kilowatt hours (kWh) of electricity consumed divided by the aggregate economic output measure of a sector, that is, a measure of average electricity use per unit of output.* Again, constant-dollar GPO is used to measure real output in the industrial and commercial sectors and constant-dollar DPI is used to measure real income for residential users. Industrial output, at 1.80 kWh per constant (1972) dollar, is now (1983) three times as electricity-intensive as commercial output, at 0.60 kWh per constant (1972) dollar. The residential sector consumed 0.69 kWh per constant (1972) dollar of DPI in 1983.

Throughout the postwar period, the intensity of electricity use in all three sectors has increased, as is shown in Figure 2-10. Between 1950 and 1983, industrial electricity intensity increased 80 percent, commercial sector intensity increased more than 180 percent, and residential intensity increased about 260 percent. Thus, electricity use was growing faster than output or income in every sector.

Although there were large increases in average electricity intensity over this total period, almost all of the growth occurred prior to 1973. Industrial and commercial sector electricity intensities increased slightly in some years after 1973, but in 1983 had fallen back to their 1973 levels. In the residential sector, electricity intensity was about 8 percent greater in 1983 than in 1973, but has not shown an appreciable increase since 1977.

Electricity Intensity within Manufacturing

Shifts in the output mix within a sector can have an important effect on the intensity of electricity use. This effect is particularly notable in manufacturing, where the electricity intensity of industry groups can vary widely.

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* Recall the discussion above of average and incremental electricity intensities.

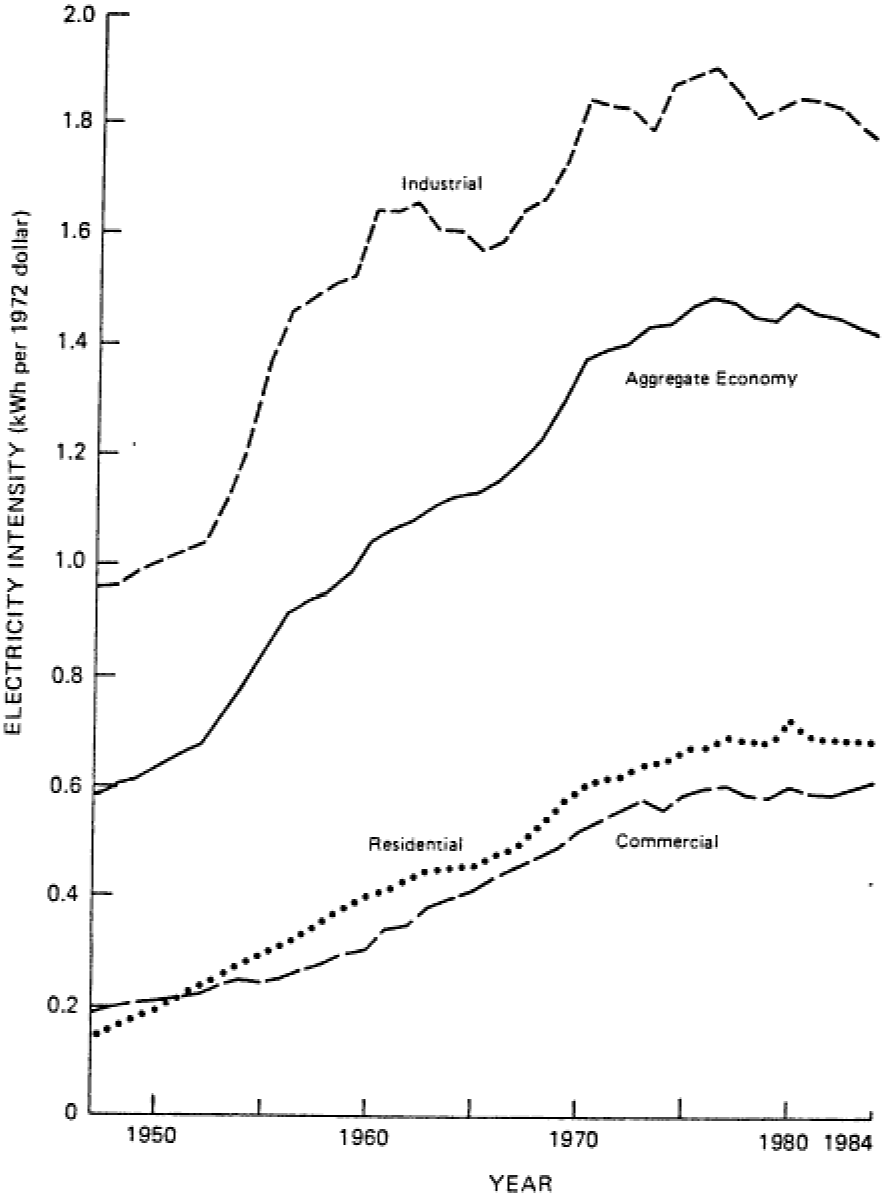

Figure 2-10 Electricity intensities in the U.S. economy, 1947 through 1984.

Sources: Based on data from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, various issues; U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

Figure 2-11 compares the electricity intensities of the six most electricity-intensive manufacturing industries with the average intensities for the rest of manufacturing and with those of the entire manufacturing sector. It can be seen that those six industries combined are about six times as electricity-intensive as the remaining industries. This figure also compares the 1973 and 1981 levels of electricity intensity for the industries; as a whole, the six industries slightly increased their electricity intensity over this period. There was also a slight reduction in electricity intensity for the rest of manufacturing and a slightly larger decrease for the entire manufacturing sector. The decrease for the entire manufacturing sector is consistent with the fact that the combined output share of the six most electricity-intensive industries has been decreasing as a percentage of total manufacturing output. Figure 2-12 illustrates this trend, and the figure also shows that the trend continued in the post-embargo period.

Thus, even with no change in the electricity intensity of the two groups of industries, electricity intensity of manufacturing tends to fall because of shifts in output mix away from the electricity-intensive group. Counteracting this tendency before 1970 was the increasing electricity intensity of both groups of industries. Since 1970, however, the historical increase in electricity intensity for the six industry groups as a whole has leveled off, while that for the rest of manufacturing has fallen about 15 percent, as Figure 2-13 shows. The primary reason for the recent drop among the latter group of industries is that these industries generally are already highly electrified, and thus efficiency improvements have outweighed any incremental penetration of electricity use (Burwell, 1983). For manufacturing as a whole, average electricity intensity has fallen over 10 percent since 1970 from a combination of both effects.

Changes in Energy Prices

Price Movements

The trend in energy prices for the 40-year period before 1973, as illustrated in Figure 2-14, was one of generally stable or decreasing prices for most fuels. Electricity Prices, in particular, declined throughout the entire period. The rapid price decline for electricity has been attributed to the increasing economies of scale in electricity generation and distribution over this period and to improvements in the efficiency (heat rate) of generation. Electricity prices were also favorably affected by the stability of primary energy input costs over the period.

Since 1973 a number of forces have combined to reverse the historical trend of declining electricity prices. First, there was the great increase in oil prices that accompanied the Arab oil embargo of 1973. This event drove petroleum product prices up immediately and also adversely affected the price of electricity in those regions of the country that depended on oil for a significant portion of their

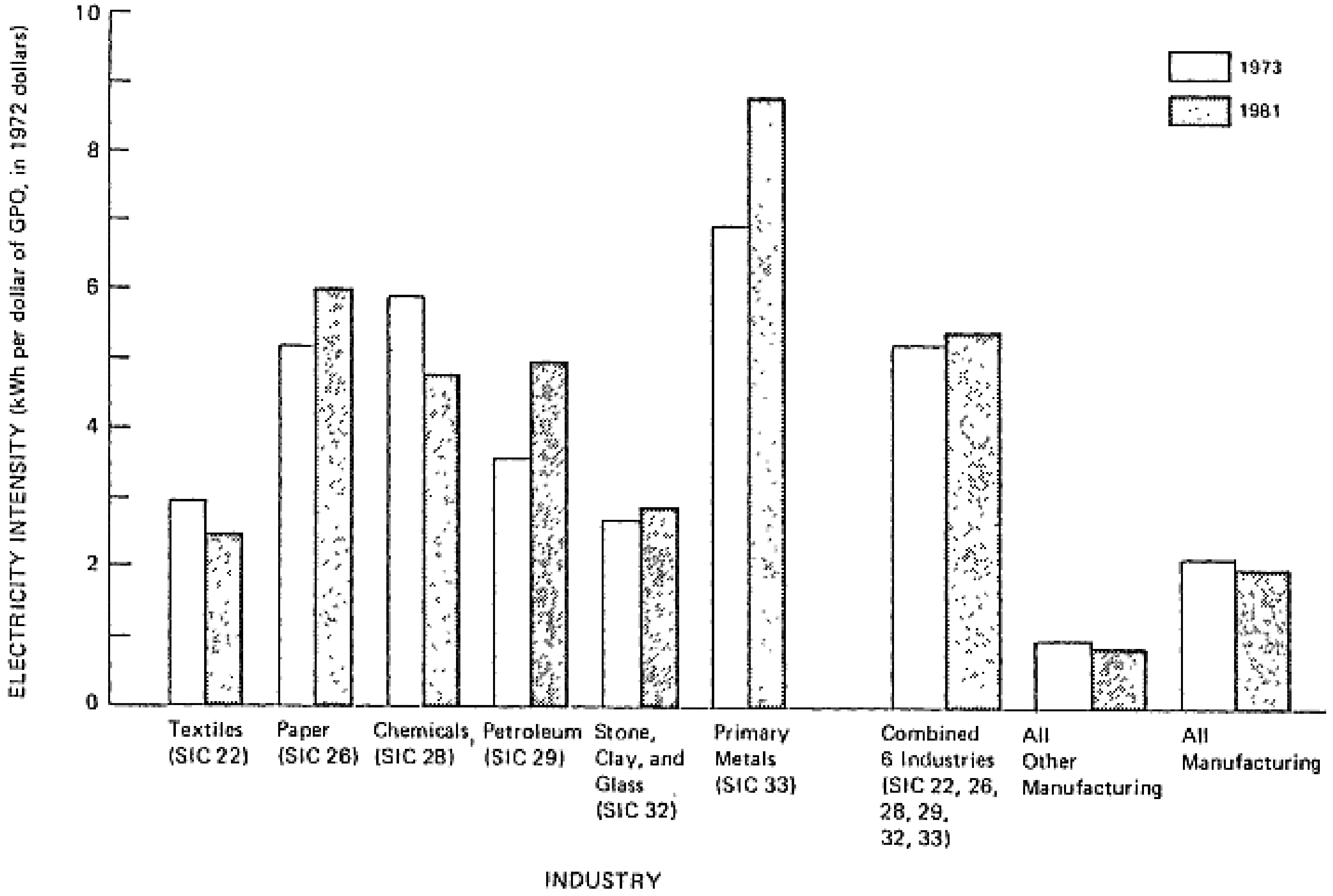

Figure 2-11
Electricity intensity of manufacturing, 1973 and 1981 compared.
Note: SIC denotes Standard Industrial Classification.
Sources: Electricity data: U.S. Department of Commerce, Bureau of the Census, Annual Survey of Manufactures: Fuels and Electric Energy Consumed. Economic data: U.S. Department of Commerce, Bureau of Economic Analysis, unpublished data provided by the Bureau.

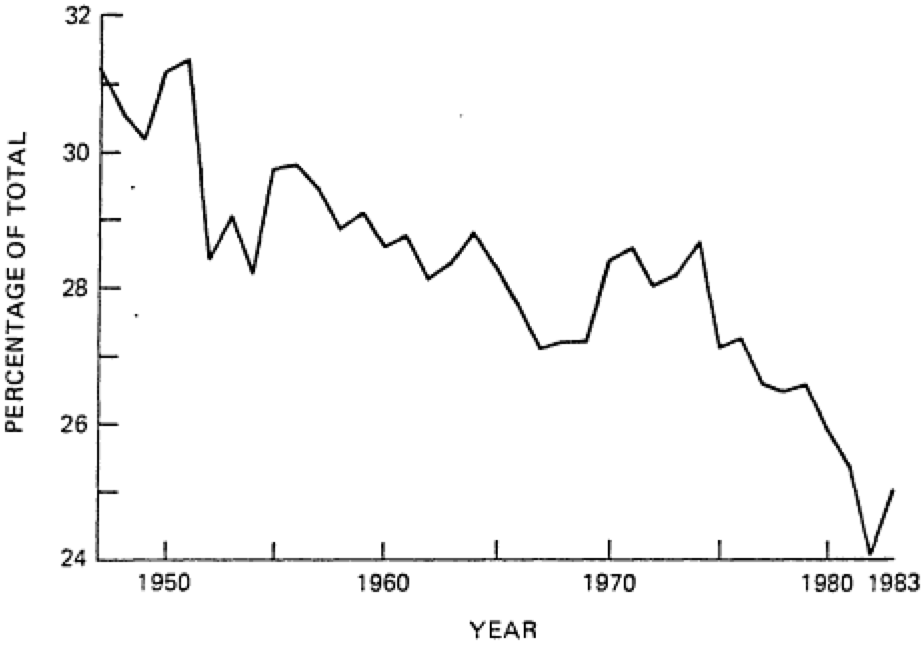

Figure 2-12
Six-SIC share of constant dollar manufacturing GPO, 1947 through 1983.
Source: Derived from unpublished data provided by the U.S. Department of Commerce, Bureau of Economic Analysis.

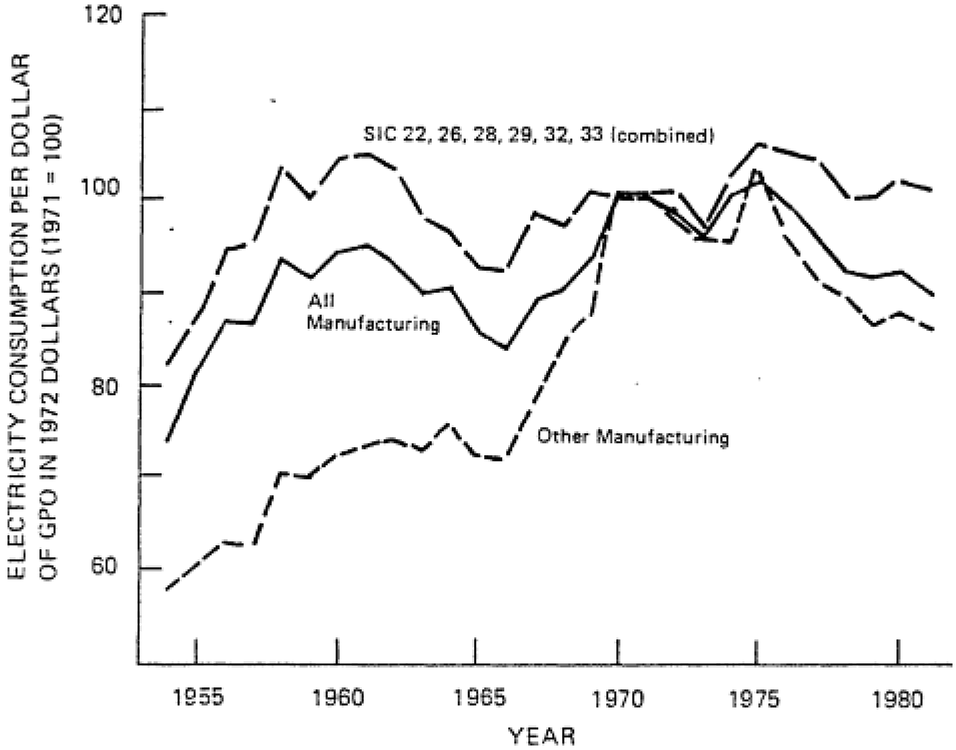

Figure 2-13
Electricity intensities in manufacturing (Index: 1971 = 100).
Source: Electricity data: U.S. Department of Commerce, Bureau of the Census, Annual Survey of Manufactures: Fuels and Electric Energy Consumed. Economic data: U.S. Department of Commerce, Bureau of Economic Analysis, unpublished data provided by the Bureau.

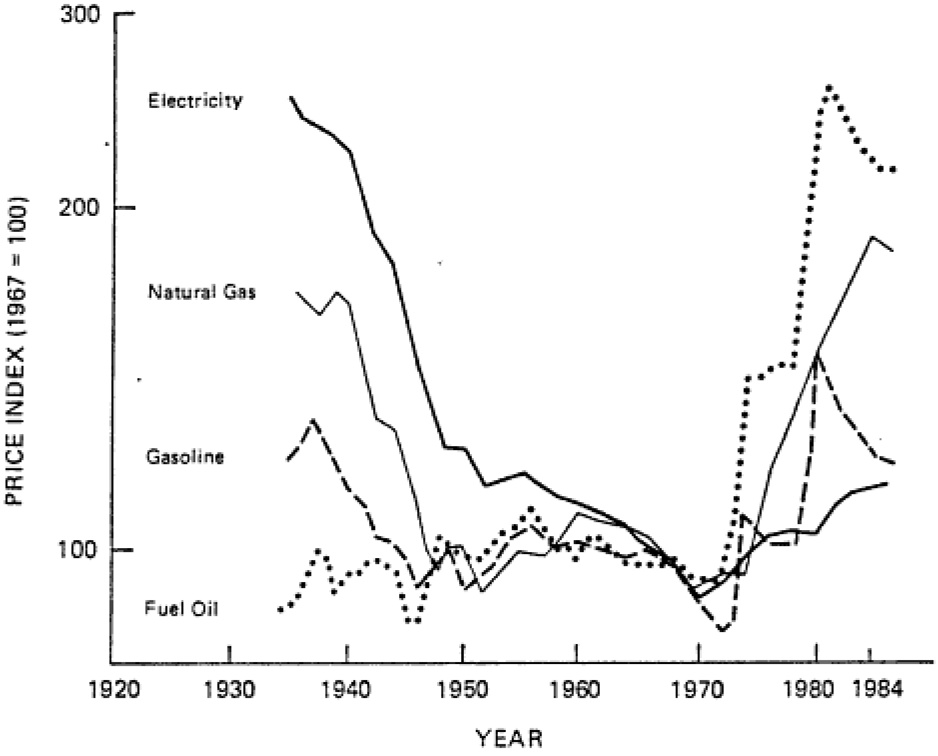

Figure 2-14
Trends in real energy prices to U.S. personal consumers, 1935 through 1984.
Note: The price indicator used is the Consumer Price Index.
Source: U.S. Department of Commerce, Bureau of the Census, Historical Statistics of the United States; U.S. Department of Labor, Bureau of Labor Statistics, Handbook of Labor Statistics 1978, Bulletin 2000; and Monthly Labor Review, various issues.

generation requirements. Figure 2-15 compares energy price trends over this period for residential and industrial consumers. The 1973 change was followed during the rest of the 1970s by a sustained rise in the price of natural gas and the second oil price shock of 1979 to 1980. The electric utility industry undertook programs during this period (with federal prodding) to cut back on both oil and natural gas as generation sources.

A second fundamental change occurred during this period: the apparent exhaustion of the economies of scale and improvements in heat rate that had led to lower per-unit costs of generation over the longer period. Power plant construction projects were also being increasingly affected by inflation and delays so that the average cost of electricity generation in many utility systems has risen as many of these new plants have come on line. An additional factor was the sharp increase in environmental regulations for power plants during the 1970s and early 1980s.

Throughout this troubled period, however, electricity price increases, on average, were only moderate. In real terms, the consumer price index (CPI) for electricity rose only 18 percent between 1973 and 1983, while the indexes for both fuel oil and natural gas more than doubled. The same trends are evident for producers. The producer price index (PPI) for electricity rose 44 percent in real terms from 1973 to 1983, while the index for petroleum rose 136 percent and the index for natural gas more than tripled.

Price increases for electricity undoubtedly have led to increases in the efficiency of electricity utilization (Edison Electric Institute, 1984b). However, there has also been a trend toward greater electricity use resulting from the substitution of electricity for oil and gas, which have been increasing in price much faster than electricity.

Figure 2-16 shows that the ratios of electricity price to the prices of oil and natural gas continued their historical decreasing trend in the post-embargo period. Studies have shown that electric resistance heating becomes more cost-effective in residences than fuel heating at existing furnace efficiencies when the ratio of electricity price to competing fuel prices reaches three or below (Burwell et al., 1982). In the aggregate, the ratio of electricity price to heating oil price has been below three since 1978 while the ratio of electricity price to natural gas price is approaching three. Of course, using electric heat pumps, electricity can be cost-effective at electricity price ratios above three. The same price trend is apparent in the industrial sector. Although energy-using technologies in this sector are quite diverse, studies have shown that the same cost-effective price ratio thresholds for electricity and oil and electricity and natural gas have already been achieved in several industries as well (Burwell, 1983).

Price Elasticities

The basically favorable relative price ratios of electricity to other fuels must be weighed against the fact that electricity price

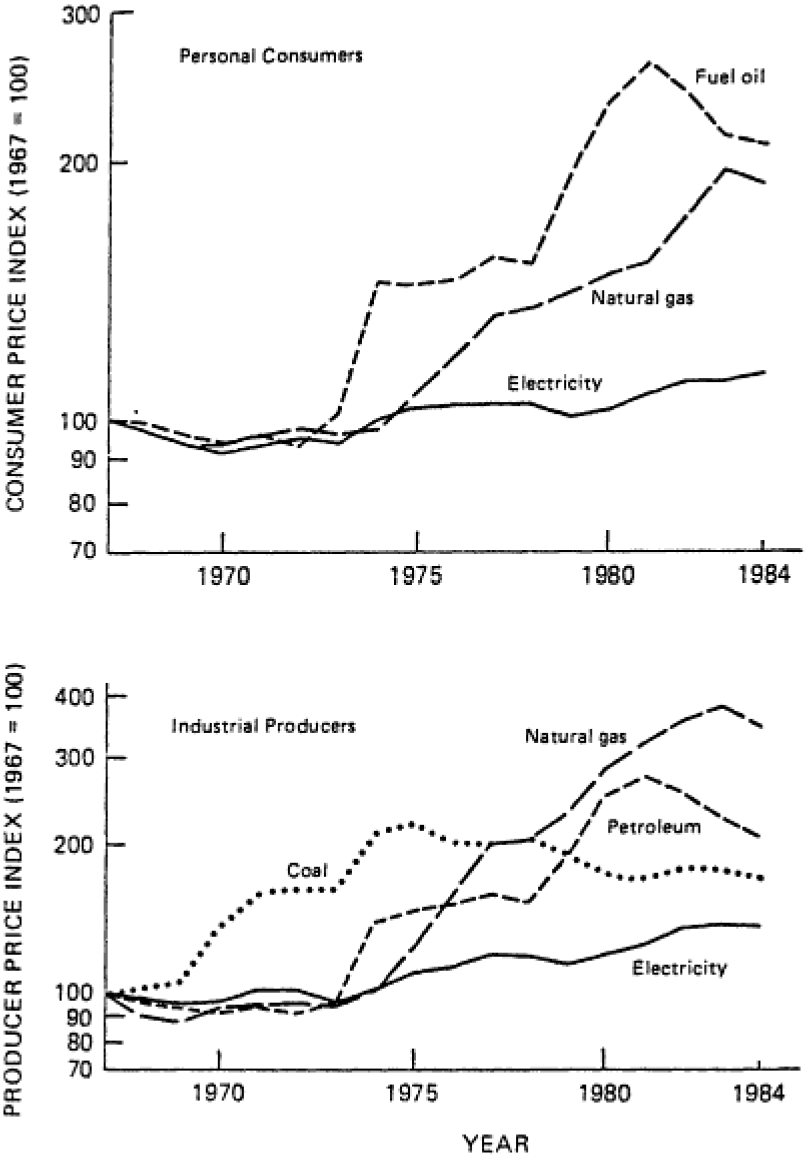

Figure 2-15
Trends in real energy prices, 1967 through 1984.
Source: U.S. Department of Labor, Bureau of Labor Statistics, Handbook of Labor Statistics, Bulletins 2000 and 2175; and Monthly Labor Review, various issues.

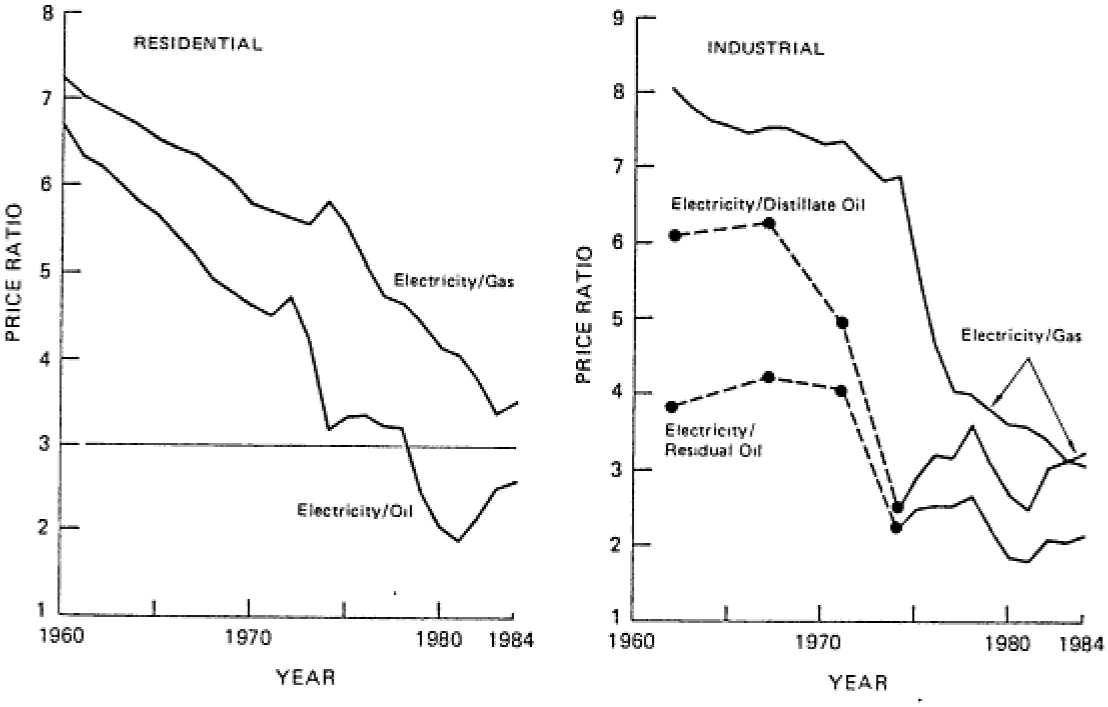

Figure 2-16

Electricity price ratios in the United States, 1960 through 1984.

Note: Price ratio calculated as ratio of actual prices in dollars per million Btu.

Sources: Based on data from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry; American Gas Association, Gas Facts; U.S. Department of Commerce, Bureau of the Census, Annual Survey of Manufactures: Fuels and Electric Energy Consumed; U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, various issues.

increases themselves also tend to discourage electricity use. It is not simply a matter of dividing a fixed energy market among electricity and other energy forms; the total market for energy may be diminished as a result of rises in all energy prices.

Econometricians have tried for years to disentangle the complex of own-price elasticity, cross-price elasticity (with other energy forms), delays in price responses, and nonprice factors such as income and changes in end-use technology. Powerful statistical tools are employed, but the results leave much to be desired. The available data base does not yet cover enough experience with high energy prices, and, in addition, theory provides very little guidance in this complex task.

Bohi (1981) provides a critical review of the methods, data, and results of the leading econometric analyses of the demand for energy forms. He finds that even for electricity, which has been subject to extensive study, "there is wide disagreement about the responsiveness of demand to changes in prices and incomes, and surprisingly broad gaps in the understanding of the nature of this process" (p. 55).

Each sector is considered separately by Bohi. In 25 studies of the residential sector, the spread of long-range, own-price elasticities was found to be -0.45 to -1.89, with a consensus value of -1.0 (that is to say, a 10-percent price increase would produce a 10-percent consumption decrease). However, after considering the methods and data employed in the studies, Bohi concludes that the best estimate for long-range residential price elasticity is -0.70 (p. 159, Table 7-1; long-range effects are usually considered as achieved in up to 10 years).

Five studies on the commercial sector are reported. Some used more than one approach, so that there are nine different sets of results. Price elasticities ranged from -1.0 to -1.60. Bohi declines to choose the most likely value, saying simply that "commercial demand appears to be price elastic in the long run. . . . " (p. 79).

Review of a broad range of industrial electricity demand studies, which used a variety of approaches, yielded a range from -0.51 to -1.82 with a consensus estimate "around -1.30." But Bohi notes that "...one has difficulty in placing much confidence in the consensus estimate" (p. 90). His own judgment, after examining the various studies, is that the price elasticity of industrial demand is between -0.5 and -1.0 (p. 159, Table 7-1).

Sweeney (1984) concludes that "the long-run delivered price elasticity of demand for electricity probably exceeds [that is, is more negative than] unity but may be as low as -0.7 (p. 36).

Bohi discusses cross-elasticity estimates but does not present numerical values. He notes that problems in the data tend to make estimates of cross-elasticities unreliable.

The most that can be safely concluded, therefore, is that own-and cross-price elasticities exist that are nonnegligible, but hard to establish precisely. As a result there are counteracting price influences on electricity demand—in particular, electricity's own price and electricity's price movements compared with those of other energy forms. In addition, of course, there are the sizable effects on the growth in electricity demand produced by the overall growth in the national output of goods and services. The net aggregative effects of all of these forces are assessed in the next section comparing pre-and post-embargo trends in electricity consumption.

CONTINUITY AND CHANGE: PRE-AND POST-EMBARGO TRENDS

The foregoing discussion shows that growth rates of electricity use have slowed in recent years from the high growth rates of earlier periods. Data for the postwar period are presented in Table 2-6.

GNP growth, averaged over recent years, has also slowed from the higher rates achieved over most of the postwar period (Table 2-6). In light of the strong association that has long been observed between electricity and GNP, viewing electricity growth rates only with respect to time can give misleading impressions.

Nevertheless, the ratio of electricity growth rates to GNP growth rates has been gradually declining (Figure 2-5), a point to which many analysts have also drawn attention. Although this trend is consistent in principle with a linear relationship between electricity use and GNP, the question remains whether the degree and rate of convergence are consistent with the trend that has characterized the entire postwar period.

Electricity price changes are frequently cited as the reason for a shift in the relationship. The econometric studies summarized above show that when the price of electricity increases it tends to slow the growth of electricity demand. However, the more recent historical period over which these statistical analyses were performed also contained the counteracting influences of rising competing fuel prices, which tend to counterbalance to some degree the effect of the electricity price increases. The extent of the competing fuel price influences on the historical relationship is less well established.

Our examination of the data leads us to believe that by far the most important contributor to the slower growth rates in electricity demand over the last decade has been lower economic growth. Others have come to a similar conclusion. The econometric analysis of Hogan (1984) shows that the primary reason for the lower growth rates in electricity demand during the 1970s was slower economic growth. He attributes only about 30 percent of the drop in electricity demand since 1972 to electricity price increases. The Edison Electric Institute (1984b) reached similar conclusions regarding the magnitude of price effects at the aggregate level. However, Hogan notes that his results capture "only part of the eventual adjustment we can expect in the gradual replacement of energy-using equipment" (p. 27). Thus, it can be expected that the energy price changes already experienced will continue to affect demand growth in the future.

The central question is, of course, what the net effect of all factors—price, income, structural change, technological advance, and so forth—has been on electricity demand in recent years and what these influences portend for the future. In our judgment, at the present time there is no clear answer to this question. Figure 2-17b

TABLE 2-6 Average Annual Growth Rates of Electricity and Gross National Product (GNP) and Their Ratios over Selected Postwar Periods

Period	Electricity Growth Rate	GNP Growth Rate	Ratio of Electricity and GNP Growth Rates
1947-1960	8.07	3.52	2.29
1960-1973	6.70	4.17	1.61
1973-1983	1.99	2.04	0.98

SOURCES: Based on data from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, various issues; U.S. Department of Commerce, Bureau of Economic Analysis, The National Income and Product Accounts of the United States, 1929-76, Statistical Tables; and Survey of Current Business, various issues.

identifies three different interpretations (depicted by lines A, B, and C) of the recent trend in electricity use as a function of GNP.

The first interpretation (line A in Figure 2-17b) is that no shift has occurred in the underlying long-term relationship, but that the data for recent years represent a "down phase" of the cycle that has persistently characterized the long-term relationship. In fact, over the postwar period it could have been inferred several times that shifts had occurred in the slope of the relationship given its cyclic movements (Figure 2-17a). Nevertheless, these inferences would have been incorrect, as shown by data for subsequent years. If the cycle continues as before, there will soon be a period when the consumption of electricity will exceed trend values. However, if the growth rate of electricity use does not exceed the growth rate of GNP over the next few years (that is, if the "down phase" is not succeeded by an "up phase"), this interpretation must be considered incorrect.

A second interpretation is that a permanent shift has occurred in the relationship, one toward a diminished increase in electricity use per dollar increment in GNP. This interpretation corresponds to a downward shift in the slope of the electricity-GNP trend line, and in fact the relationship can be read in such a way as to support this belief (Figure 2-17b, line B, which is an extension of the uppermost arrow on Figure 2-17a).

Still another interpretation is that the increase in the rate of structural change between the industrial and commercial sectors and within manufacturing in recent years will neither be corrected nor proceed at the same rate in the future. If the future shift were to revert to the slower historical postwar rate and the sectoral electricity intensity relationships continue to hold, then the effect on the electricity-GNP trend would be a parallel downward shift in the postwar trend line (an intercept shift), leaving the slope coefficient intact (Figure 2-17b, line C).*

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* If this result occurs, it would be a mirror image of the transition from the relationship of the 1920s to that of the 1930s. Incremental electricity intensity did not change between the two periods, as can be seen from the parallel lines of regression for the two periods (Figure 2-3). Because the percentage decreases in GNP in the years immediately following 1929 were larger than the percentage decreases in electricity use, average electricity intensity actually increased. However, as the years passed the trend of the 1930s turned out to be parallel to that of the 1920s. The net result of the change in average intensity was simply a shift in the line parallel to itself (mathematically, a shift of the intercept). At the time that the shift occurred, there was of course no way of knowing that this outcome would result. Likewise, only time will tell whether the line of the future will fall below and parallel to the line representing 1947 through 1973. Such behavior would reflect a decrease in average intensity as a result of price effects, conservation, and the permanent decline of some energy-intensive industries, with any lingering effects of past price rises being offset by the tendencies toward increased electrification already discussed.

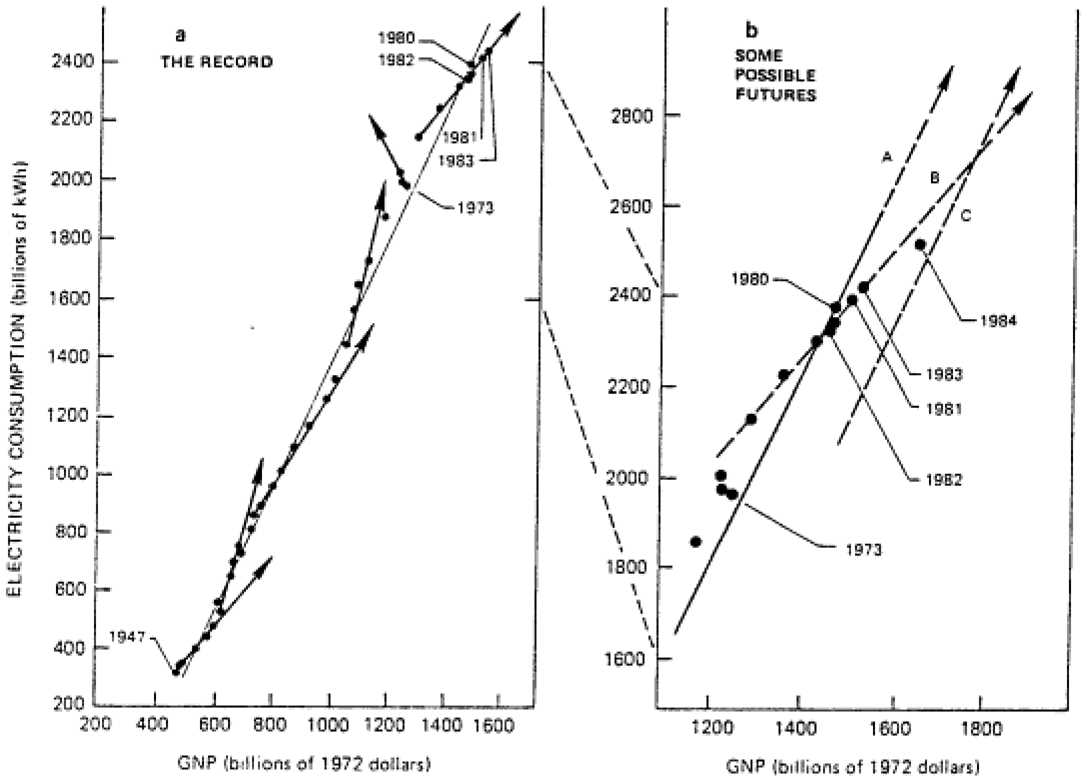

Figure 2-17
Electricity vs GNP: (a) the 1947-1983 record, (b) some possible future relationships.
Note: The long-term trend line in the left figure is the same as in Figure 2-4. The lines with the arrowheads in this figure indicate how the trend seemed to be changing at various times in the past based on short-term movements of the data. However, these movements turned out to be aberrations, and there was 4 always a reversion to the underlying long-term trend.

The figure to the right depicts three possible interpretations of the recent past, none of which can be proved or disproved at the present time. Line A is a continuation of the basic long-term trend of the main figure; line B is a continuation of the short-term trend starting in 1976; line C is a new trend line. Line C assumes that the decline in average electricity intensity that occurred through 1984 represents a lasting change, but that incremental intensities will revert to the basic trend (see text for further discussion and for a historical parallel). Cyclic and random variations (e.g., because of weather) around any future trend line will still occur, no matter what the trend line turns out to be.

It will be several years before these questions are resolved. The post-embargo years are still too few to provide definitive answers about trend shifts. In the meantime, however, the historical record suggests that the electrification of the economy will continue. Indeed, electricity use has continued to increase in all sectors over the post-embargo period while fuel consumption more generally either has been stable or, as in most cases, has fallen, as is shown in Figure 2-18. Furthermore, our examination of the major consuming sectors indicates that substantial potential remains within these sectors for the continued penetration of electricity in many uses.

Generally, the rates of growth in electricity use will depend on the strength and growth of the economy. That much is clear. The exact quantification of this relationship for the current period and its relevance to future trends are important questions that remain to be settled.

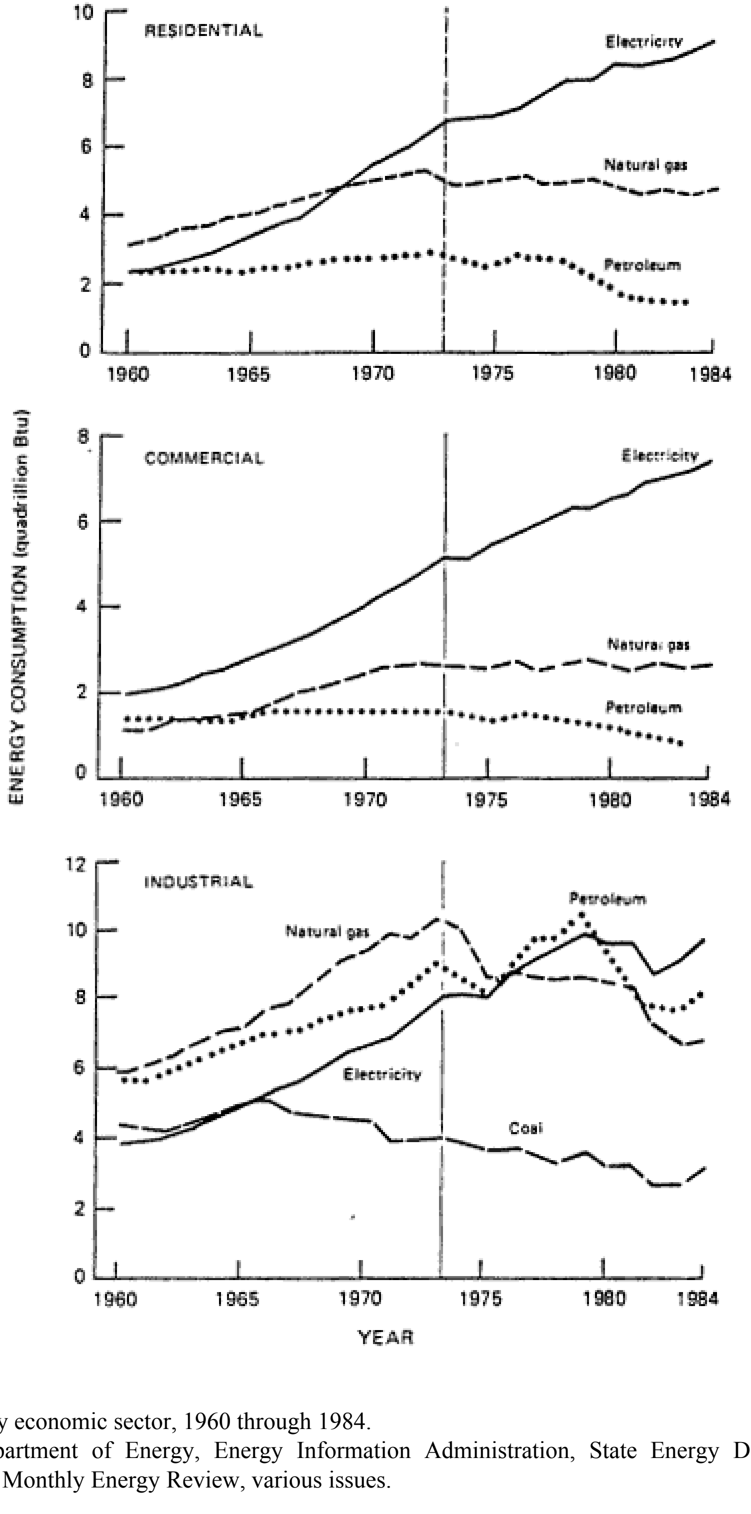

Figure 2-18
Gross energy use by economic sector, 1960 through 1984.
Sources: U.S. Department of Energy, Energy Information Administration, State Energy Data Report, DOE/EIA-0214(83); and Monthly Energy Review, various issues.

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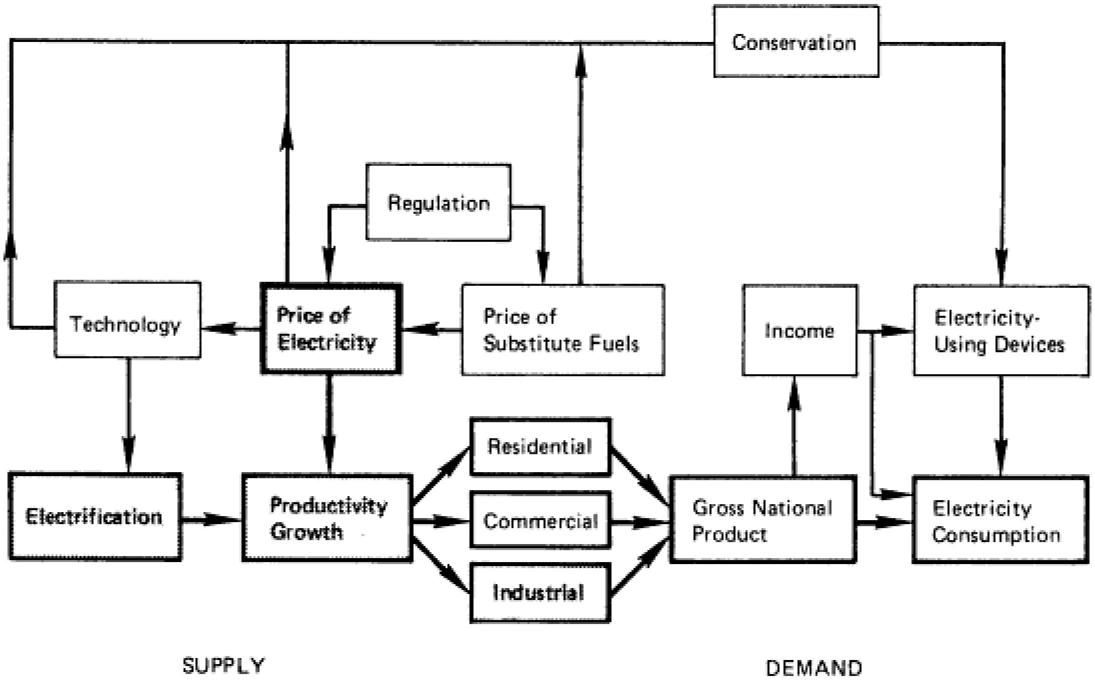
3

Electricity and Productivity Growth*



The objective of this chapter is to analyze the role of electricity in the growth of productivity. The chapter touches on the shaded portions of the above reproduction of Figure 1-1.

The concept of productivity figures prominently in analyzing economic growth. The relationship between electricity and

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* Much of the content of this chapter is based on Jorgenson (1984) and is incorporated here because of its special relevance to the committee's task.

productivity began in the early decades of this century with the widespread electrification of many industrial processes, as described in the preceding chapter. Beginning in the 1970s, the decline in growth of the world's major economies, which followed the increase in prices of all forms of energy, demonstrated forcefully that the role of energy in economic growth should be more fully evaluated.

Statistics for the United States show that decline in aggregate productivity growth contributed importantly to the decline in aggregate economic growth. Aggregate productivity rests on productivity of individual sectors of the economy, and these sectoral productivities are amenable to analysis.

By adopting an econometric model of some generality, it has been possible to estimate empirically the quantitative dependence of sectoral productivity growth on technical change and the prices of the several inputs to production, including electrical and nonelectrical energy. For many industries, technical change is found to increase the shares, relative to those of other inputs to production, that given changes in electrical and nonelectrical energy input values contribute to change in output value. For such industries, technical change is said to be "electricity using" and "energy using," that is, it tends to increase the relative shares of electricity and nonelectrical energy in the value of output. For the same industries, lower prices of these inputs, in association with technical change, are found to enhance productivity growth.

The significance of this analysis is that it provides an interpretation of the recent decline in economic growth in terms of higher energy prices associated with the Arab oil embargo of 1973. In addition, for the purposes of this study, the analysis provides increased insight into the interaction of electricity and economic growth and suggests areas for further research.

The material of this chapter helps support one of the principal conclusions of the study, namely:

- Productivity growth may be ascribed partly to technical change; in many industries technical change also tends to increase the relative share of electricity in the value of output, and in these industries productivity growth is found to be the greater the lower the real price of electricity, and vice versa.

THE CONCEPT OF PRODUCTIVITY

Productivity means output per unit of input. In this sense, productivity corresponds to the engineer's concept of efficiency.

Confusion may arise in characterizing productivity unless the measures of output and input are clearly specified. At the level of individual industries in the economy, output is often expressed in physical units. For example, steel need not be measured in terms of monetary value added to iron—an economist's abstraction—but may be measured simply in tons. The output of the motor vehicle industry may be measured in numbers of vehicles produced. Similarly, the output of the petroleum industry may be measured in barrels of petroleum, and so forth. It is also convenient to represent output by the monetary value (that is, the product of quantity and unit price) of the physical product. In fact, such a representation is needed if the outputs of diverse industries are to be compared. Inputs may be measured in physical quantities also, but to be compared they also have to be expressed in terms of their values.

Since the output of production results from various input factors such as capital, labor, and energy, it is possible to define a partial productivity with respect to any one input. For example, labor productivity is defined as output per unit of labor input, the measures of both being specified, such as dollar value of goods produced per employee-hour worked. Energy productivity and electricity productivity may be defined similarly. In fact, electricity productivity, measured in constant dollar value of output per kilowatt hour of electricity input, is just the reciprocal of the quantity electricity intensity, introduced in Chapter 2. Total factor productivity is the ratio of some measure of output to some measure of all inputs—capital, labor, energy, materials, and so forth.

Economists analyze the growth of output at the sectoral level in terms of the contributions of capital and labor inputs to a sector and the contributions of inputs to that sector produced by other sectors. Inputs produced by other sectors include both the raw materials and the energy that are produced by any given set of businesses and supplied to other sets. Growth of output also results from improvements in productivity.

The idea of productivity growth at the sectoral level is close to the engineering concept of an increase in efficiency, and it is an easy idea to appreciate intuitively. Output, measured by its monetary value at producers' prices, say, may be considered a function of the various inputs, again measured in terms of their values. Fractional growth of output is allocable to contributions from the growth of each input, plus a contribution ascribed to productivity growth. Productivity growth may result from substitution of a cheap input for an expensive one to achieve the same measure of output for a smaller total measure of input. Productivity growth may also be achieved through technical change that of itself increases output or decreases input. Of course, substitution and technical change may occur simultaneously.

Output at the level of total economic activity is given as gross national product (GNP), measured in dollars. Capital and labor inputs are the so-called primary factors of production that generate the whole of economic activity.

To decompose economic growth (that is, percentage change in GNP) into its sources, we allocate growth among three components. The percentage growth of an economy is a combination of the percentage growth in productivity and the contributions of growth in capital input and labor input. Growth in capital input represents the increased stocks of capital equipment and structures that result from investment. Growth in labor input represents an increase in the labor force, in hours worked per employee, in the education and experience of the labor force as reflected in higher wage rates, or any combination of these. As a matter of interest, in the United States the most important source of economic growth is the contribution of capital input. Growth in capital input accounts for about half of the growth that has taken place. The contribution of growth in labor input is the least important because of the stability of the labor force. The magnitude of productivity growth falls in between.

Gains in the efficiency of production at the industry level will accumulate in the economy as a whole to provide greater growth of output than can be accounted for by the growth in both capital and labor inputs. Thus, productivity growth for the whole economy is defined as the residual after accounting for the contributions of growth in capital and labor inputs to the growth of output. In engineering terms, productivity growth at the level of the entire economy may be thought of as the aggregate increase in the efficiency with which economic resources are used at lower levels.

THE BACKGROUND

The special significance of energy in economic growth was first established in the classic study, Energy and the American Economy, 1850-1975: Its History and Prospects (Schurr et al., 1960). Although this study covered only the United States, the experience of other industrialized countries is similar in many ways. In this study Schurr and his colleagues noted that, between 1920 and 1955, the energy intensity of production (defined as energy consumed per unit of GNP, and hence the reciprocal of energy productivity) fell in the United States, while both labor productivity and total factor productivity were rising.* The simultaneous decline in energy and labor intensities of production ruled out explaining the growth of productivity solely by the substitution of cheap energy for expensive labor.

To explain the growth of output given declining energy and labor intensities required examining the character of productivity growth, engendered largely by technical change. Such an examination was further suggested by the fact that from 1920 to 1955 the use of electricity had grown more than 10-fold, while the consumption of all other forms of energy only doubled.

The two most important features of technical change concerning electricity during this time were, first, that the thermal efficiency of conversion of fuels into electricity increased by a factor of three and, second, that "the unusual characteristics of electricity had made

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* This discussion is also based on Schurr (1983). Berndt (1985) analyzed energy intensity and productivity growth in U.S. manufacturing for 1899 to 1939.

it possible to perform tasks in altogether different ways than if those fuels had to be used directly" (Schurr, 1983, p. 205). Schurr emphasized the impact of the electrification of industrial processes, yielding much greater flexibility in applying energy to industrial production.*

The importance of electrification in productivity growth was also documented by Rosenberg (1983):

> Increasingly, the spreading use of electric power in the 20th century has been associated with the introduction of new techniques and new arrangements which reduce total costs through their saving of labor and capital. Perhaps the most distinctive features of these new techniques are (1) that they take so many forms as to defy easy categorization, and (2) that they occur in so many industries that they defy a simple summary.

Rosenberg illustrates this point with examples drawn from the production of iron and steel, glassmaking, and the production and use of aluminum.

Rosenberg, like Schurr and his associates, draws attention to the significance of electrification of industrial processes that was taking place during the first several decades of the century. Notably, electrical motors provided greater flexibility in supplying power to industrial processes and in organizing and physically arranging them. Rosenberg (1983, p. 295) reaches the following general conclusion concerning technical change that may rely more on electricity and less on labor:

> It seems obvious that there has been a very wide range of labor saving innovations throughout industry which have taken an electricity using form. As a consequence, greater use of electricity is, from an historical point of view, the other side of the coin of a labor saving bias in the innovation process.

Schurr (1982, 1984) recently extended the analysis of Energy and the American Economy, 1850-1975 through 1981. In this analysis, his assessment of the period 1953 through 1969 was as follows (1982, p. 6):

> Although the inverse relationship between total factor productivity and energy intensity virtually disappeared during the 1953 to 1969 period, it is still noteworthy that high rates of improvement in total factor productivity were essentially not associated with increases in energy intensity.

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* Recall from the discussion in Chapter 1 that electrification refers to the adoption of processes and activities based on the use of electricity. The term alone does not necessarily imply increased (or decreased) electricity consumption.

In his later analysis Schurr also assessed the experience of the U.S. economy in the aftermath of the oil embargo of 1973. He points out that the energy intensity of production has fallen steadily since 1973 and that the rate of decline accelerated sharply after the second oil price shock in 1979, following the Iranian revolution. He then makes the following point (1982, p. 10):

> While energy productivity has been improving at a very high rate during the past decade, the overall productive efficiency side of the story has been highly unfavorable, and has become a matter of great concern. The post-1979 years that witnessed a new high in the rate of growth of national energy productivity also saw a decline in productive efficiency with a fall in total factor productivity of about 0.3 percent per year between 1979 and 1981.

We can summarize this evidence about the relation between energy intensity and productivity growth by saying that energy intensity was falling while productivity was rising between 1920 and 1953. Between 1953 and 1969 energy intensity was relatively stable, while productivity continued to rise. After 1973 energy intensity resumed its downward trend, dropping faster after 1979, while productivity growth fell beginning in 1973, and turned into actual productivity decline after 1979.

In exploring the determinants of trends in energy intensity and productivity growth, a useful framework is provided in the original study by Schurr et al. (1979), Energy in America's Future. This study emphasizes the role of change in the composition of national output, trends in energy intensity for industrial sectors, the significance of changes in the form of energy employed, and the role of energy prices. Chapter 2 of this report gave some attention to these points. Focusing on developments from 1975 through 1977, Schurr and his associates conclude that changes in the composition of national output offer "a useful but, at best, limited insight" (p. 88). They also find that energy intensity has declined in some sectors and risen in others (pp. 89-90). They find that the transformation of energy forms, especially in the direction of greater electrification and the use of fluid forms of energy such as petroleum and natural gas, has played an important role in economic activity: "[Such] changes have made possible shifts in production techniques and locations within industry, agriculture, and transportation that greatly enhanced the growth of national output and productivity" (p. 92). Finally, they argue that "quite apart from energy prices, technology developed its own momentum" (ibid.).

The framework suggested by Schurr and his associates and the historical evidence on trends in energy intensity and productivity growth suggest that explaining these trends must encompass a wide range of determinants. First, the gradual decline in real energy prices through the early 1970s and the sharp increases in energy prices that followed the oil shocks of 1973 and 1979 suggest an important role is played by the substitution that may occur between energy and other productive inputs, especially labor input. While the real price of labor input rose steadily during the early 1970s, this price has been declining since that time. These price trends would suggest that substitution of energy for labor occurred during the early 1970s and that substitution of labor for energy occurred thereafter.

Second, productivity growth is an important element in explaining trends in energy intensity. In this regard, Schurr reviewed U.S. experience through 1969 as follows (1982, p. 9):

> The net result, then, was that strong improvements in both energy productivity and overall productive efficiency were achieved without any special efforts being made to bring about this desirable combination of circumstances. Energy was abundantly available, and its price was low and, for the most part, falling during this period. Simple economic reasoning would tell us that the intensity of energy use should have risen because favorable energy prices would have encouraged energy consumption. But even though energy use rose relative to labor inputs, it fell in relationship to the final output of the economy. Did this decline in energy intensity take place in spite of low energy prices, or somehow because of them?

The mechanisms of productivity growth, as described above by Schurr and by Rosenberg, indicate a specific role for electrification. Further understanding should result by analyzing the roles of the prices of both electricity and nonelectrical energy in determining productivity growth.

THE RECENT DECLINE IN ECONOMIC GROWTH

To assess the effects of energy prices on economic growth, we begin with a brief review of several decades before the first oil crisis.

World Economies*

Rapid economic growth in the industrialized countries through 1973 has resulted in unprecedented world economic prosperity. An extreme example is provided by the Japanese economy, which between 1960 and 1973 grew at the astonishing rate of 10.9 percent per year. This growth quadrupled Japan's GNP, moving Japan from the ranks of the developing countries to its current status as a major industrial power.

The largest industrialized economies of Europe participated fully in the great economic boom of the 1960s and early 1970s. The GNPs of France and Germany grew at 5.9 and 5.4 percent per year, respectively,

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* This section is based on Christensen et al. (1980, 1981), who compare patterns of economic growth in industrialized countries.

between 1960 and 1973. This rapid growth in Germany followed the "economic miracle" of 1952 through 1960, when Germany's GNP grew at 8.2 percent per year, exceeding even Japan's GNP growth at 8.1 percent per year during that time. From 1960 to 1973 Italy's GNP grew at 4.8 percent per year, while the United Kingdom's rate was a respectable 3.8 percent per year. The leading industrialized countries of Europe more than doubled their GNPs after World War II.

By comparison, in North America the U.S. GNP grew at 4.3 percent per year from 1960 to 1973, and Canada's GNP grew at 5.1 percent per year during that time. In Europe the rapid economic growth took place with negligible growth in hours worked, while in North America hours increased at approximately 1.5 percent per year. The 1960s and 1970s also witnessed rapid growth among developing countries; GNP growth rates greater than 5 percent per year were not uncommon. Korea provided another extreme example, its GNP growing at 9.7 percent per year between 1960 and 1973, so that this country's economic expansion almost matched that of Japan.

The impact of the first oil crisis on economic growth in industrialized countries was disastrous. GNP growth in the member countries of the Organisation for Economic Co-operation and Development (OECD) as a whole plummeted to 2.6 percent per year from 1973 to 1979. GNP growth in the United States dropped slightly less than the OECD average. GNP growth in Japan fell from its double digit rates of the 1960s and early 1970s to 3.9 percent per year—to almost the same rate as that of the United Kingdom, the slowest growing of industrialized countries from 1960 to 1973. The rate of GNP growth in Germany fell to 2.4 percent per year for the period 1973 to 1979, while GNP growth in France during this period was only 3.1 percent per year.

The U.S. Economy

To analyze in more detail the decline in U.S. economic growth following the first oil crisis, we can begin by decomposing the growth of output for the entire economy into the contributions of capital input, labor input, and productivity growth.* The results are given in Table 3-1 for the postwar period 1948 through 1979 and for a number of subperiods, each chosen because it represents a major business cycle.

The first part of Table 3-1 provides data on growth in output and in capital and labor inputs. The second part of the table gives the contributions of capital and labor inputs to output growth. The third part of the table presents a decomposition of the rate of productivity growth for the U.S. economy as a whole. This growth rate is a weighted sum of productivity growth rates at the level of individual industrial sectors and the contributions of reallocations of value

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* An analysis of the slowdown in productivity growth in industrialized countries is given by Lindbeck (1983).

TABLE 3-1 Relative Annual Growth of Various Quantities in the U.S. Economy for Selected Periods, 1948 through 1979

	1948-1979	1948-1953	1953-1957	1957-1960	1960-1966	1966-1969	1969-1973	1973-1979
Growth								
Growth in value added	0.0344	0.0394	0.0305	0.0266	0.0450	0.0323	0.0318	0.0292
Growth in capital input	0.0404	0.0516	0.0389	0.0269	0.0366	0.0487	0.0414	0.0378
Growth in labor input	0.0148	0.0160	0.0023	0.0100	0.0199	0.0185	0.0116	0.0197
Rate of productivity growth	0.0090	0.0092	0.0128	0.0095	0.0180	0.0008	0.0078	0.0019
Contributions								
Contribution of capital input	0.0171	0.0208	0.0165	0.0114	0.0158	0.0210	0.0174	0.0161
Contribution of labor input	0.0084	0.0093	0.0012	0.0056	0.0112	0.0106	0.0066	0.0111
Reallocations								
Sectoral rates of productivity growth	0.0083	0.0177	0.0147	0.0115	0.0162	0.0013	0.0044	-0.0072
Reallocation of value added	0.0021	-0.0067	0.0018	0.0002	0.0018	0.0011	0.0048	0.0017
Reallocation of capital input	-0.0005	-0.0015	0.0008	0.0006	0.0004	-0.0007	-0.0009	-0.0019
Reallocation of labor input	-0.0009	-0.0003	-0.0010	-0.0028	-0.0005	-0.0010	-0.0005	-0.0008

SOURCE: Fraumeni and Jorgenson (1984).

added, capital input, and labor input among sectors to productivity growth for the economy as a whole.

We have taken value added by capital and labor inputs to be the measure of output for the aggregate U.S. economy. Between 1948 and 1979, aggregate value added grew at 3.44 percent per year, while capital input grew at 4.04 percent per year, indicating that the ratio of capital to output rose during that time. By contrast, over the same time labor input grew at only 1.48 percent per year, and the productivity growth rate was 0.90 percent per year.

The average growth rate of value added reached its high at 4.83 percent per year during the period 1960 to 1966; it grew at only 2.92 percent per year during the recession and recovery of 1973 to 1979. The growth of capital input was stabler, exceeding 5 percent per year from 1948 to 1953 and 1966 to 1969 and falling to 3.78 percent per year from 1973 to 1979. Growth of labor input reached a high of 1.99 percent per year in the period 1960 to 1966, falling only to 1.97 percent per year from 1973 to 1979, a value well above the postwar average growth rate. Finally, the productivity growth rate was at its high from 1960 to 1966, at 1.80 percent per year. In the following period, from 1966 to 1969, the productivity growth rate was almost negligible at 0.08 percent per year. This rate recovered during 1969 to 1973, rising to 0.78 percent per year; finally, the rate of productivity growth fell to 0.19 percent per year between 1973 and 1979.

To provide additional perspective on the sources of U.S. economic growth, we next analyze the contributions of capital and labor inputs to the growth of value added. The contribution of each input is equal to the product of its growth rate and the average value share (or weight) of the input in value added.* Since the average subperiod value shares of capital and labor inputs remained fairly constant between 1948 and 1979, the changes of these contributions among subperiods largely parallel those in the growth rates of capital and labor inputs.

For the entire period 1948 through 1979, the contribution of capital input, at 1.71 percent per year, is the most important source of growth in aggregate value added. The productivity growth rate is the next most important source, at 0.90 percent per year, while the contribution of labor input is the third most important source, at 0.84 percent per year. The contribution of capital input is the most important source of growth during six of the seven subperiods, all those but that from 1960 to 1966, during which time the productivity growth rate is the most important source of economic growth.

The decline in the growth rate of aggregate value added between the two periods 1960 to 1966 and 1966 to 1969 appears to result primarily

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* Analytically, if $\text{in } G = v_K \text{ In } K + v_L \text{ In } L + \text{in } P$, where G is aggregate value added, K is capital input, L is labor input, P is productivity, and v_K and v_L are the value shares for capital and labor inputs respectively, then $\text{din } G = v_K \text{ din } K + v_L \text{ d in } L + \text{d in } P$.

from a dramatic fall in the rate of aggregate productivity growth between these periods. The growth of capital input actually increased, while the growth of labor input declined only slightly. The revival of productivity growth during 1969 through 1973 was offset by declines in the growth of capital and labor inputs, leaving the growth rate of value added almost unchanged. The productivity growth rate declined gain between 1973 and 1979.

Thus the decline in growth of value added since 1966 has been associated with productivity growth rates that are the lowest of the postwar period.

U.S. Productivity Growth

As noted above, the productivity growth rate for the U.S. economy as a whole can be decomposed into four components—a weighted sum of the rates of sectoral productivity growth and reallocations of value added, capital input, and labor input. The weights reflect the contribution of productivity growth in each sector to the growth of output in that sector. The weights also reflect the contribution of productivity growth to the growth of inputs to each sector that are produced by the other sectors. The contribution of the reallocation of value added to aggregate productivity growth involves the redistribution of value added among sectors from low value to high value components of output. Similarly, reallocations of capital and labor inputs involve the redistributions of these inputs among sectors from low remuneration to high remuneration uses.

For the entire period from 1948 to 1979, sectoral rates of productivity growth account for almost all of the rate of aggregate productivity growth. The reallocation of value added is 0.21 percent per year, while reallocations of capital and labor inputs are -0.05 and -0.09 percent per year, respectively.

The collapse in the rate of aggregate productivity growth after 1966 resulted from a drop in the weighted sum of sectoral rates of productivity growth from 1.62 to 0.13 percent per year from the period 1960 to 1966 to the period 1966 to 1969. Between 1969 and 1973 sectoral rates of productivity growth recovered to 0.44 percent per year; the most important contribution to reviving the aggregate productivity growth rate between those two periods was the increase in the reallocations of value added from 0.11 percent per year in the period 1966 to 1969 to 0.48 percent per year in the period 1969 to 1973. Between 1973 and 1979 the weighted sum of sectoral rates of productivity growth declined to -0.72 percent per year.

To summarize these findings about the decline in U.S. economic growth during the past decade, we can see that this decline took place in two steps. First, productivity growth at the sectoral level essentially disappeared as a source of economic growth after 1966. A very sizable decline in sectoral productivity growth rates began in the period 1966 through 1969 and persisted through 1973. Second, between 1973 and 1979 sectoral productivity growth rates plummeted.

Whatever the causes of the decline, they are to be found in the collapse of productivity growth at the sectoral level rather than in a decline in the growth of capital and labor inputs at the aggregate level or in the reallocations of value added, capital input, or labor input among sectors. However, our measure of sectoral productivity growth is simply the unexplained residual between growth in sectoral output and the contributions of sectoral capital, labor, energy, and materials inputs. The problem remains of explaining the fall in productivity at the sectoral level.

THE ECONOMETRIC MODEL

Our general conclusion from reviewing postwar U.S. economic history is that understanding the role of energy in productivity growth or decline requires analyzing productivity growth by individual industrial sectors. As Rosenberg and Schurr have indicated, this analysis should encompass the substitution of electricity for other forms of energy. Schurr has suggested that the relatively lower electricity prices (compared to those of other forms of energy) that have accompanied the dramatic increases in thermal efficiency of electricity generation have been an important force in electrification. The relative price reduction and ensuing electrification have accelerated the productivity growth rate through innovations in many industrial activities.

A Model of Sectoral Productivity Growth

The Form of the Model

To assess the role of energy in stimulating productivity growth, it is necessary to do more than merely describe the trends in energy use and in productivity. For this purpose we employ an econometric model of sectoral productivity growth. Details are given in Appendix C. In assessing the significance of changes in the form of energy employed, we identify the inputs for each sector as capital, labor, electricity, nonelectrical energy, and materials. Our econometric model treats the substitution among productive inputs in response to changes in relative prices. The model also determines sectoral productivity growth rates as a function of relative prices.

For each industry our model of production is based on a sectoral price function (Appendix C, Equation 1) that encompasses possibilities for substitution among inputs as well as patterns of technical change. Each price function gives the price of output for an industrial sector as a function of the prices of capital, labor, electricity, nonelectrical energy, and materials inputs and, in addition, time; in this formulation time represents the level of technology in the sector (Samuelson, 1953). Thus the passage of time represents technical change. Obviously, when there is an increase in the price of one input, and the prices of the other inputs and the level of technology remain unchanged, there must be an increase in the price of output. Similarly, if the productivity of a sector improves, say, through a change in the level of technology, and the prices of all sectoral inputs remain the same, the price of output must fall. Price functions summarize these and other relationships among the prices of output, capital, labor, electricity, nonelectrical energy, and materials inputs, and in addition the level of technology.

Sectoral price functions provide a complete model of production patterns for each sector. We find it useful to express the model in two parts. First, we can express the value shares of changes in each of the five inputs—capital, labor, electricity, nonelectrical energy, and materials—in the change of output value as functions of the prices of these inputs and time, again representing the level of technology (Appendix C, Equations 3).* Second, supplementing these five equations for the value shares, we can obtain an equation that expresses productivity growth rate as a function of the prices of all five inputs and time (Appendix C, Equation 4). This equation is our econometric model of sectoral productivity growth (Jorgenson, 1985; a useful survey of studies relating energy prices and productivity growth is given by Berndt, 1982).

Parameters of the Model

As in any econometric model, the relationships determining the value shares of capital, labor, electricity, nonelectrical energy, and materials inputs and the productivity growth rate involve unknown parameters (Appendix C, Equations 2) which must be estimated from data for the individual industries. Among these unknown parameters are the so-called biases of productivity growth (Appendix C, Equations 6), which indicate the effects of change in the level of technology (that is, technical change) on the value shares of each of the five inputs. (Hicks, 1932, introduced the concept of bias of productivity growth; an alternative definition was introduced by Binswanger, 1974a, 1974b. The definition employed in our econometric model is discussed by Jorgenson, 1985.)

The biases of productivity growth for each of the five inputs appear as the coefficients of time, again, representing the level of technology, in the five equations for the value shares of each kind of input. For example, the bias of productivity growth for capital input

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* Our sectoral price functions are based on the transcendental logarithmic (or translog) price function introduced by Christensen et al. (1971, 1973). The translog price function was first employed for sectoral analysis by Berndt and Jorgenson (1973) and Berndt and Wood (1975). Berndt and Wood (1979) provide references to sectoral production studies encompassing energy and materials inputs.

gives the change in the value share of capital input in response to change in the level of technology, represented by time.* We say that technical change, or productivity growth, which is proportional to technical change, is capital using if the bias of productivity growth for capital input is positive. That is, technical change would tend to increase the relative share of capital in the value of output. Similarly, we say that productivity growth is capital saving if the bias of productivity growth for capital input is negative.

It is important to observe that the sum of the biases of all five inputs must be zero (Appendix C, Equations 2), since the changes in all five value shares with a change only in technology must sum to zero (from Appendix C, Equation 8). That is, if productivity growth is electricity using, then productivity growth must be input saving in some other input. For example, productivity growth could be labor saving and electricity using, as suggested by the quotation from Rosenberg cited earlier. This last example would be represented by a positive bias of productivity growth for electricity and a negative bias of productivity growth for labor. Our econometric model, then, classifies each of the 35 industries of our study among the 30 logically possible patterns of productivity growth, that is, all the possible combinations of positive or negative values for each of the five biases. We can rule out only the possibility that all five biases are negative and that all five are positive, on the basis of purely analytical considerations.

We have pointed out that our econometric model yields an equation (Appendix C, Equation 4), for each industrial sector of the U.S. economy, giving the sectoral productivity growth rate as a function of the prices of the five inputs and time (or level of technology). The same biases of productivity growth that appear in the value share equations also appear as coefficients of the prices in the equation for the sectoral productivity growth rate. This feature of our econometric model makes it possible to use information about changes in the sectoral value shares with time and about changes in the sectoral productivity growth rate with prices in estimating the biases of productivity growth.

The model also contains alternative interpretations of the biases of productivity growth. The first interpretation is as the rate of change of the value share of each input with respect to time. This interpretation focuses on the biases of productivity growth as the coefficients of time in the equations for the value shares, that is, each bias is the weight of the level of technology in that value share (Appendix C, Equations 3). The second interpretation is as the rate of change of the negative of sectoral productivity growth rate with respect to proportional input prices. This interpretation focuses on the biases of productivity growth as the coefficients of prices in the equation for the negative of productivity growth rate, that is, each

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* In other words, the bias of productivity growth for capital is the weight of the level of technology as one contribution to the value share of capital, and similarly for other inputs.

bias is the weight of the price of the corresponding input in the negative productivity growth rate (Appendix C, Equation 4). The two interpretations are equivalent, since the value shares and the productivity growth rate are both generated from an underlying price function for each sector.

In other words, the biases of productivity growth express the dependence of the value shares of the five inputs on the level of technology and also express the dependence of the productivity growth rate on the prices. Thus, capital-using productivity growth, represented by a positive bias of productivity growth for capital input, means that an increase in the price of capital input decreases the productivity growth rate. Analogous relationships hold for the biases of labor, electricity, nonelectrical energy, and materials inputs.

Modeling the Role of Electricity in Productivity Growth

In assessing the role of electricity in productivity growth, the critical parameter in our econometric model is the bias of productivity growth for electricity (Appendix C, β_{ET}). This bias gives the change in the value share of electricity in response to changes in the level of technology (that is, technical change). We say that productivity growth (or technical change) is electricity using if the bias of productivity growth for electricity is positive. Similarly, we say that productivity growth is electricity saving if the bias of productivity growth for electricity input is negative. Thus, to test the hypothesis that productivity growth is electricity using for a particular industrial sector, we evaluate the bias of productivity growth for electricity along with other parameters describing substitution and technical change in that sector. We then test the hypothesis that the bias of productivity growth is positive.

The dual role of the bias of productivity growth—expressing the effect of technical change on the value share of an input and the effect of change in price of that input on the productivity growth rate—is central to our assessment. Historical evidence, as summarized by Rosenberg, suggests that much of the innovation in the twentieth century is electricity using. That is, innovation increases the share of electricity in the value of output for a given set of input prices, including that of electricity. Entirely different evidence, analyzed by Schurr and his associates, has linked the reduction in the cost of electricity, from increasing thermal efficiency in electricity generation, to enhanced productivity growth. Within our econometric model these two instances of historical evidence are consistent with the hypothesis that the bias of productivity growth for electricity is positive.

According to the model, electricity-using productivity growth (or technical change), associated with a positive bias of productivity growth for electricity, means that electricity use tends to increase as technology changes. This is what occurred during the first several decades of this century, according to the evidence reviewed by Rosenberg. Electricity-using productivity growth also implies that the rate of productivity growth increases as the price of electricity declines, which is consistent with the historical evidence on the growth of output, productivity, and energy consumption analyzed by Schurr.

This historical evidence suggests the hypothesis that technical change at the level of individual sectors of the U.S. economy is electricity using. This relationship implies that electricity plays a central role in productivity growth. It remains to test the hypothesis using our model.

Results from the Model

Applying the Model

To apply our econometric model of production we assembled a data base for 35 industries in the U.S. economy (Jorgenson and Fraumeni, 1981). These industries encompass all sectors of the U.S. economy. Manufacturing is subdivided among 21 industries at the two-digit level of the Standard Industrial Classification. These industries differ greatly in their relative importance to the economy and in their energy intensities of production. The complete set of industries also encompasses the primary production sectors of agriculture and mining; the energy-intensive transportation and public utilities industries; and the construction, communications, trade, and service industries.

For capital and labor inputs we first compiled data by sector on the basis of the classification of economic activities employed in the U.S. National Income and Product Accounts. We then transformed these data into a format appropriate for the classification of activities employed in the U.S. Interindustry Transactions Accounts. Regarding electricity, nonelectrical energy, and materials inputs, we compiled data by sector on interindustry transactions among the 35 industrial sectors. For this purpose we used the classification of economic activities employed in the U.S. Interindustry Transactions Accounts. *

The data on capital inputs employed in this study are based on estimates of the stock of capital goods for each of the 35 industrial sectors. For each sector we prepared estimates for corporate and noncorporate business, separated into four asset types—producers' durable equipment, nonresidential structures, inventories, and land. Stocks of capital goods, broken down by legal form of organization and type of asset are aggregated by property compensation for each type of capital. Estimates of property compensation incorporate data on rates

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* Data on energy and materials are based on annual interindustry transaction tables for the United States, 1958 through 1974, compiled by Jack Faucett Associates (1977). Data on capital and labor inputs are based on estimates by Fraumeni and Jorgenson (1984). These data have been updated through 1979 by Jorgenson (1984).

of return for each sector, rates of revaluation of each type of asset, and variables that describe the tax structure for each type of capital input. Measures of capital input are obtained by aggregating over both legal forms of organization and all four types of asset for each sector.

Our measures of labor input are based on data on hours worked and labor compensation for each industrial sector, cross-classified by sex, age, education, employment status, and occupation of workers. Control totals for each industry are based on surveys of business establishments. To disaggregate labor input by demographic characteristics we exploited the detail on employment, hours worked, weeks paid, and compensation available from household surveys. For each year the complete distributions of hours worked and labor compensation are broken down by 81,600 categories. Measures of labor input are obtained by aggregating over both sexes, eight age groups, five levels of educational attainment, two employment classes, and ten occupational categories within each industry.

For each sector we compiled annual data on the value shares of capital, labor, electricity, nonelectrical energy, and materials inputs, for 1958 through 1979. We also compiled price indexes for sectoral outputs and all five sectoral inputs for the same period. Finally, we compiled transcendental logarithmic indexes of sectoral rates of productivity growth. There are 21 observations for each equation since unweighted two-period averages of all data are employed.

The sample period contains changes in energy prices that were momentous by any standard. The data set includes 7 years, 1973 through 1979, out of a total of 22 years, 1958 through 1979, that can be characterized as a period of high energy prices. The results, as reported in detail by Jorgenson (1984), show very low standard errors on the key parameters relating energy prices to productivity growth. One reason for this precision is the sharp increase in energy prices and the equally sharp decline in productivity growth after 1973.

Estimating the Biases of Productivity Growth

We first consider the bias of productivity growth with respect to the price of capital input, using the dual interpretations explained previously. Technical change is capital using for 20 of the 35 industries included in our study; it is capital saving for the other 15. We conclude that the productivity growth rate decreases with the (increasing) price of capital input for 20 industries and increases with this (increasing) price for 15 industries.

Interpreting the biases of productivity growth with respect to the prices of labor, electricity, nonelectrical energy, and materials inputs is analogous to interpreting the bias with respect to the price of capital input. Considering the bias of productivity growth with respect to the price of labor input, we find that technical change is labor using for 26 of the 35 industries and labor saving for 9 of these industries. Hence the productivity growth rate decreases with the price of labor input for the 26 industries and increases with this price for the other 9.

Considering the bias of productivity growth with respect to the price of electricity input, we find that technical change is electricity using for 23 of the 35 industries included in our study and electricity saving for 12. Hence the productivity growth rate decreases as the price of electricity rises for the same 23 industries and increases as this price rises for the same 12.

Turning to the bias of productivity growth with respect to the price of nonelectrical energy input, we find that technical change is nonelectrical energy using for 28 of the 35 industries and nonelectrical energy saving for only 7. We conclude that the productivity growth rate decreases with the price of nonelectrical energy for 28 industries and increases with this price for the remaining 7.

Finally, technical change is materials using for 8 of the 35 industries and materials saving for the other 27. Thus, the rate of productivity growth increases with the increasing price of materials for 27 industries and decreases with this price for the remaining 8.

Patterns of the Biases of Productivity Growth

Table 3-2 classifies industries by their patterns of biases of productivity growth. The most frequent pattern of the biases corresponds to technical change that is capital using, labor using, electricity using, nonelectrical energy using, and materials saving. This pattern occurs for 8 of the 35 industries. In this pattern the productivity growth rate decreases with increasing prices of capital, labor, electricity, and nonelectrical energy inputs and increases with increasing price of materials input. The second most frequent pattern corresponds to technical change that is capital saving, labor using, electricity using, nonelectrical energy using, and materials saving. This pattern occurs for 5 industries. In this pattern the productivity growth rate decreases with increasing prices of labor, electricity, and nonelectrical energy inputs and increases with increasing prices of capital and materials inputs. These two patterns of the biases of productivity growth differ only in the role of the price of capital input.

The Hypothesis Concerning Electricity and Productivity Growth

We have estimated biases of productivity growth with respect to prices of capital input, labor input, electricity input, nonelectrical energy input, and materials input. These biases are undetermined parameters of the econometric models for the 35 industrial sectors included in this study. To test the hypothesis advanced by Schurr and Rosenberg about the importance of electrification in productivity growth, we

TABLE 3-2 classification of Industries by Their Patterns of Biases of Productivity Growth

Pattern of Biases	Industries
Capital using	Tobacco, textiles, apparel, lumber and wood, printing and publishing, fabricated metal, motor vehicles, transportation
Labor using	
Electricity using	
Nonelectrical energy using	
Materials saving	
Capital using	Electrical machinery
Labor saving	
Electricity using	
Nonelectrical energy using	
Materials using	
Capital using	Metal mining, services
Labor using	
Electricity using	
Nonelectrical energy saving	
Materials saving	
Capital using	Nonmetallic mining, miscellaneous manufacturing, government enterprises
Labor using	
Electricity saving	
Nonelectrical energy using	
Materials saving	
Capital using	Construction
Labor saving	
Electricity using	
Nonelectrical energy saving	
Materials using	
Capital using	Coal mining, trade
Labor using	
Electricity saving	
Nonelectrical energy saving	
Materials saving	
Capital using	Agriculture, crude petroleum and natural gas, petroleum refining
Labor saving	
Electricity saving	
Nonelectrical energy using	
Materials saving	

Pattern of Biases	Industries
Capital saving Labor using Electricity using Nonelectrical energy using Materials using	Food, paper
Capital saving Labor using Electricity using Nonelectrical energy using Materials saving	Rubber; leather; instruments; gas utilities; finance, insurance, and real estate
Capital saving Labor using Electricity saving Nonelectrical energy using Materials using	Chemicals
Capital saving Labor saving Electricity using Nonelectrical energy using Materials using	Transportation equipment and ordnance, communications
Capital saving Labor using Electricity saving Nonelectrical energy using Materials saving	Stone, clay, and glass; machinery
Capital saving Labor using Electricity using Nonelectrical energy saving Materials saving	Primary metals
Capital saving Labor saving Electricity using Nonelectrical energy using Materials saving	Electric utilities
Capital saving Labor saving Electricity saving Nonelectrical energy saving Materials using	Furniture

focus on the bias of productivity growth with respect to electricity input. Recall that if this bias is positive, then technical change is electricity using; if the bias is negative, technical change is electricity saving. If technical change is electricity using, the value share of electricity input in the value of output increases with technical change, while the productivity growth rate increases with a decrease in the price of electricity.

We have found that technical change is electricity using for 23 of the 35 industries included in our study. Our first and most important conclusion is that electricity plays a very important role in productivity growth. A decline in the price of electricity stimulates productivity growth in 23 of the 35 industries and dampens productivity growth in only 12. Alternatively and equivalently, we can say that technical change results in an increase in the share of electricity input in the value of output, holding the relative prices of all inputs constant, in 23 of the 35 industries. Technical change results in a decrease in the share of electricity input again in only 12.

Our empirical results provide strong confirmation of this hypothesis about the relationship of electrification and productivity growth in a wide range of industries. Schurr et al. (1979) have shown that the price of electricity fell in real terms through 1971. This decline in real electricity prices promoted electricity use through the substitution of electricity for other forms of energy and through the substitution of energy for other inputs, especially for labor. In addition, the decline in the real price of electricity stimulated the growth of productivity in a wide range of industries. The spread of electrification and the rapid growth of productivity through the early 1970s are both associated with a decline in real electricity prices. This decline was made possible in part by advances in the thermal efficiency of electricity generation.

Beginning in the early 1970s the downward trend in the real price of electricity reversed. This reversal has been associated with a marked decline in advancing the thermal efficiency of electricity generation, a decline which began in the late 1960s. However, the diminishing rate of technical change in the electricity-generating industry only partly explains the reversing trend in real electricity prices. In addition, the prices of primary energy sources employed in electricity generation rose sharply following the oil price shocks of 1973 and 1979. Rising electricity prices, then, have slowed productivity growth in U.S. industries throughout the 1970s. These price increases play an important role in explaining the decline of U.S. productivity growth since 1973.

Subsidiary Hypotheses

In linking electrification and productivity growth, Schurr advanced an important subsidiary hypothesis, namely, that electrification is especially significant in stimulating productivity growth in the manufacturing industries. Schurr's hypothesis is supported by the fact that technical change is electricity using in 15 of the 21 manufacturing industries included in our study, while technical change is electricity using in only 8 of the 14 nonmanufacturing industries. Schurr's explanation for this phenomenon is that the electrification of industrial processes led to much greater flexibility in the application of energy. Rosenberg's examples of the importance of electrification—in iron and steel, glass, and aluminum production—are also drawn from manufacturing.

Rosenberg advanced another subsidiary hypothesis in analyzing the link between electrification and productivity growth. This hypothesis is that electricity-using technical change is the "other side of the coin" of labor-saving technical change. We have been unable to find support for this hypothesis in our empirical results. In fact, technical change is labor saving for only 9 of the 35 industries and labor using for the remaining 26. However, we have pointed out that the sum of biases of productivity growth for all five inputs must equal zero. The predominance of electricity-using technical change therefore must be balanced by technical change that saves other inputs. We have found that technical change is materials saving for 27 of the 35 industries and materials using for only the remaining 8. For all other inputs, including labor and electricity, technical change is predominantly input using. We conclude that technical change that uses electricity input and inputs of capital, labor, and nonelectrical energy is balanced by technical change that saves materials.

Nonelectrical Energy and Productivity Growth

We have found that electricity plays an important role in productivity growth, and we have also examined the use of nonelectrical energy. Our findings are that technical change is nonelectrical energy using for 28 of the 35 industries included in our study and nonelectrical energy saving for 7 of these industries. A decline in the price of nonelectrical energy stimulates productivity growth in 28 of the 35 industries and dampens productivity growth in only 7. Correspondingly, we can say that technical change results in an increase in the share of nonelectrical energy input in the value of output in 28 of the 35 industries and results in a decrease in nonelectrical energy input share for only 7.

Again considering the evidence on energy price developments presented by Schurr and his associates, we find that the price of nonelectrical energy fell in real terms through the early 1970s, reaching a minimum for natural gas and fuel oil in 1970 and for gasoline in 1972. This decline in real nonelectrical energy prices promoted greater use of nonelectrical energy through the substitution of these forms of energy for capital, labor, and materials inputs. In addition, the decline in the real price of nonelectrical energy, like the decline in electricity prices we examined earlier, stimulated the growth of productivity in a wide range of industries. We conclude that the greater use of nonelectrical energy in relation to other inputs such as labor and the rapid growth of productivity through the early 1970s are associated with the decline in the real price of nonelectrical energy.

Beginning in the early 1970s the downward trend in the real price of nonelectrical energy reversed, and the increase in use of nonelectrical energy relative to other inputs in U.S. industries slowed dramatically. This reversal in the trend of nonelectrical energy prices, as well as an important part of the reversal in the trend of electricity prices examined above, was associated with the oil price shocks of 1973 and 1979. Rising prices of nonelectrical energy have reinforced the negative effects of rising electricity prices on productivity growth throughout the 1970s. Increases in the real prices of both electricity and nonelectrical energy help explain the decline in U.S. productivity growth since 1973.

In linking greater use of nonelectrical energy with productivity growth, Schurr et al. (1979) advanced another important subsidiary hypothesis: that greater use of fluid forms of energy has enhanced productivity in agriculture, transportation, and manufacturing. We find that technical change is nonelectrical energy using in agriculture and transportation, as suggested by Schurr and his associates. We also find that technical change is nonelectrical energy using for 19 of the 21 manufacturing industries included in our study. Technical change is nonelectrical energy using for only 7 of the 12 industries other than agriculture, manufacturing, and transportation. We conclude that greater use of nonelectrical energy has a significant role in productivity growth for an even wider range of industries than has the use of electrical energy.

Summary

We have now completed our analysis of the role of electrical and nonelectrical energy in productivity growth employing an econometric model of production. Given the framework of our model we can offer a tentative explanation of the disparate trends in energy intensity and productivity growth. These trends first drew the attention of Schurr and his associates to the special role of electrification. Between 1920 and 1953 energy intensity of production was falling while productivity was rising. While the fall in real prices of electricity and nonelectrical energy resulted in substitution of energy inputs for other inputs, especially for labor, these price trends also generated sufficient growth in output per unit of energy input that the energy intensity of production fell. This explanation is consistent with that advanced by Schurr and his associates.

Between 1953 and 1973 energy intensity was stable, while productivity continued to grow. During this period real energy prices continued to fall, but at slower rates than between 1920 and 1953. As before, the fall in real prices of electricity and nonelectrical energy resulted in the substitution of energy inputs for other inputs. Yet these increases were almost completely matched by the growth in output per unit of energy input, leaving the energy intensity of production unchanged. Finally, real energy prices began to rise in the early 1970s, increasing dramatically after the first oil shock of 1973 and again after the second oil shock of 1979. These price trends resulted in substitution of capital, labor, and materials inputs for inputs of electricity and nonelectrical energy, thereby reducing energy intensity of production. At the same time, energy price trends contributed to a marked decline in productivity growth.

Although much research is still required to understand the role of energy use in productivity growth, our analysis has made progress toward that goal. We have analyzed the character of productivity growth in industries representing the whole U.S. economy. We have tested hypotheses advanced in earlier research, by Schurr and his associates and by Rosenberg, with empirical evidence and found support for the hypothesis that electrification and productivity growth are related. We have found that the use of nonelectrical energy and productivity growth are even more strongly related. Pursuit of this inquiry should provide a deeper understanding of the relationship between energy use and productivity change.

Given support for the hypothesis that technical change is electricity using and nonelectrical energy using, we can assess the potential for electrification and greater use of nonelectrical energy in reviving productivity growth at the level of individual industries in the United States. Schurr has summarized this potential as follows (1982, p. 7):

> If this line of theorizing is correct, one of the keys to reconciling the future growth of energy productivity and labor and total factor productivity would be (a) through the vigorous pursuit of these energy supply technologies which assure the renewed future availability, on favorable terms, of those energy forms which possess the highly desirable flexibility features that have characterized liquid fuels and electricity, and (b) through the search for counterpart energy consumption technologies that can put these characteristics to efficient use in industrial, commercial, and household applications.

INTERPRETATION OF THE RECENT DECLINE IN GROWTH

The sharp decline in economic growth in industrialized countries presents a problem comparable in scientific interest and social importance to the problem of mass unemployment in the Great Depression of the 1930s. Conventional methods of economic analysis that look only at aggregate changes in productivity have been tried and found inadequate. Clearly a new framework based on understanding changes at the sectoral level will be required. The findings we have presented contain some of the elements for analyzing the prospects for the world economy in the last half of the 1980s.

At first sight the finding that higher energy prices are an important determinant of the decline in economic growth seems paradoxical. In studies of sources of aggregate economic growth, energy appears as both an output and an input for individual industries, but cancels out for the economy as a whole.* It is necessary to disaggregate the sources of economic growth by sector to define the correct role of energy in economic growth.

Within such a framework for analyzing economic growth, it is still not sufficient to decompose the growth of sectoral output among the contributions of inputs and of productivity growth. It is essential to explain the growth of sectoral productivity. In the absence of such an explanation the growth of sectoral productivity is simply an unexplained residual between the growth of output and the contributions of growth of capital, labor, electricity, nonelectrical energy, and materials inputs.

Finally, the significance of energy prices for sectoral productivity growth must be determined empirically. From a conceptual point of view, energy prices can have positive, negative, or no effects on sectoral productivity growth. From an empirical point of view, the influence of higher energy prices has been negative and highly significant. This empirical finding can be substantiated only through an econometric model of productivity growth.

The steps we have outlined—disaggregating the sources of economic growth by sector; decomposing the growth of sectoral output into productivity growth and the contributions of capital, labor, electricity, nonelectrical energy, and materials inputs; and modeling the growth of productivity—have been taken only recently. Although much additional research is required to explain the decline of economic growth in industrialized countries, we find it useful to employ this framework in assessing future growth prospects for industrialized countries.

We begin by comparing our methods with alternative approaches to energy demand forecasting. A gradual decline in real energy prices through 1973 provided a mild stimulus to the growth of energy demand. However, rapid economic expansion in the industrialized world and in the less developed countries provided by far the main source of energy growth. Forecasts of energy demand were based on projections of economic growth with little or no attention to energy prices. This method of energy demand forecasting prevailed up to the time of the first energy crisis in 1973.

The Arab oil embargo of late 1973 and early 1974 resulted in a dramatic increase in world oil prices. Between 1973 and 1975 crude oil import prices increased by two and one-half times in real terms for the seven major OECD countries—Canada, France, Germany, Italy,

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* A leading proponent of this view is Denison (1984). Comparisons of studies of energy and productivity by Berndt (1985), Jorgenson (1984), and Schurr (1984) are given by Sonenblum (1985) and Wood (1985).

Japan, the United Kingdom, and the United States.* Japan was the country most affected by the oil price increases, experiencing a tripling of real crude oil import prices. Of European countries France was not far behind Japan in experiencing increases in the real price of crude oil imports.

Real energy prices to final users increased considerably less than did real oil prices in all major OECD countries. The average increase for these seven countries from 1973 to 1975 was 23.9 percent. Japan and Italy were at the high end of the range, with increases in excess of 50 percent. Meanwhile, Canada experienced only a 3.9 percent increase under a regime of price controls on domestic petroleum and natural gas. Similar controls in the United States did not prevent an increase of 23 percent in real energy prices to final users.

The Iranian revolution beginning in late 1978 sent a second wave of oil price increases through world markets. Between 1978 and 1980 crude oil import prices almost doubled in real terms for the seven major OECD countries. Real energy prices to final users climbed by 33.5 percent for these countries. Again, Japan was hard hit with an 80.3 percent increase, while Canada experienced an increase of only 8.7 percent. In the United States, the real price increase was 34 percent, while major European countries had increases below the average.

Energy analysts generally agreed that the great discovery emanating from the first oil crisis was the price elasticity of demand for energy. One of the first post-embargo projections of energy demand in the United States was provided by the Energy Policy Project. This projection featured two low energy growth scenarios—a "technical fix" scenario, exploiting available technologies to achieve energy conservation, and a "zero per capita energy growth" scenario, featuring energy growth at the same rate as population growth.

Although the low energy growth scenarios presented by the Energy Policy Project met with considerable skepticism in 1974, the zero per capita energy growth scenario actually overestimated U.S. energy consumption in 1980, only six years later, by 15 percent. By 1982 U.S. energy demand had fallen below the level that prevailed in 1972 before the first oil crisis. U.S. oil consumption fell even more dramatically, declining to 1971 levels by 1982. The world price of petroleum was taken to be exogenous by the Energy Policy Project (Hudson and Jorgenson, 1974a, 1974b). Although the price increases associated with the first oil crisis were taken into account, the additional increases after the Iranian revolution were not included in the analysis. As a consequence, energy demands were overestimated.

Methods for energy demand forecasting that take account of the price elasticity of energy demand became commonplace by the end of the 1970s. However, the new orthodoxy was itself overtaken by events.

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* Fujime (1983) compares energy prices and energy demand patterns in industrialized countries. Hogan (1984) provides projections of U.S. energy demand.

The oil price increases that accompanied the Arab oil embargo presented a unique challenge to economic policymakers. Some policy analysts interpreted price increases from whatever source as inflationary. Careful students of open economy macroeconomics pointed out the deflationary impact of an increase in the price of an imported commodity—oil.

As the debate among policy analysts continued, policymakers were hesitant to take precipitate action. With inflation at double digit levels in 1973 anti-inflationists held ground in the United States well into the first oil crisis. As a consequence, the deflationary impact of oil price increases was reinforced by tight monetary and fiscal policy, leading to the most severe economic decline since the Great Depression. As unemployment rose, orthodox Keynesianism experienced a brief revival, only to be banished with the resulting "stagflation"—combined economic stagnation and inflation.

By 1978, after the first oil crisis, economists began to analyze the role of energy prices in economic change. The central theme that emerged was the substitution between energy and other productive inputs—especially labor and capital inputs (Hudson and Jorgenson, (1978a, 1978b; Jorgenson, 1983b). Economists recalled that energy and capital are complements if an increase in the price of energy reduces the demand for both energy and capital, while energy and labor are substitutes if an increase in energy prices leads to an increase in the demand for labor.

It transpired that energy and capital are on the borderline between substitution and complementarity, so that the increase in energy prices left the demand for capital largely unaffected. Of course, the short-run effect of higher prices for imported petroleum was to reduce the return to capital, which is fixed in supply. However, energy and labor proved to be highly substitutable, so that the demand for labor rose with increases in energy prices. In Europe, this effect resulted in an increase in real wages, since labor supply was inelastic with respect to price. In the United States, the increase in labor demand led to unprecedented increases in employment.

By 1981 it was clear that the concept of substitution between energy and other productive inputs, combined with the analysis we have presented of energy prices and productivity growth, could explain the decline in economic growth in industrialized countries (Jorgenson, 1983a, 1984). The process of substitution requires five to seven years, since the accumulation or decumulation of capital stock takes time. The process of adjustment to the second world oil crisis has now been completed in most industrialized countries. However, the effect of higher energy prices on productivity is permanent and has led to widespread declines in productivity growth. As a consequence, the growth prospects for industrialized countries have been permanently reduced to levels below those that prevailed from 1973 to 1979.

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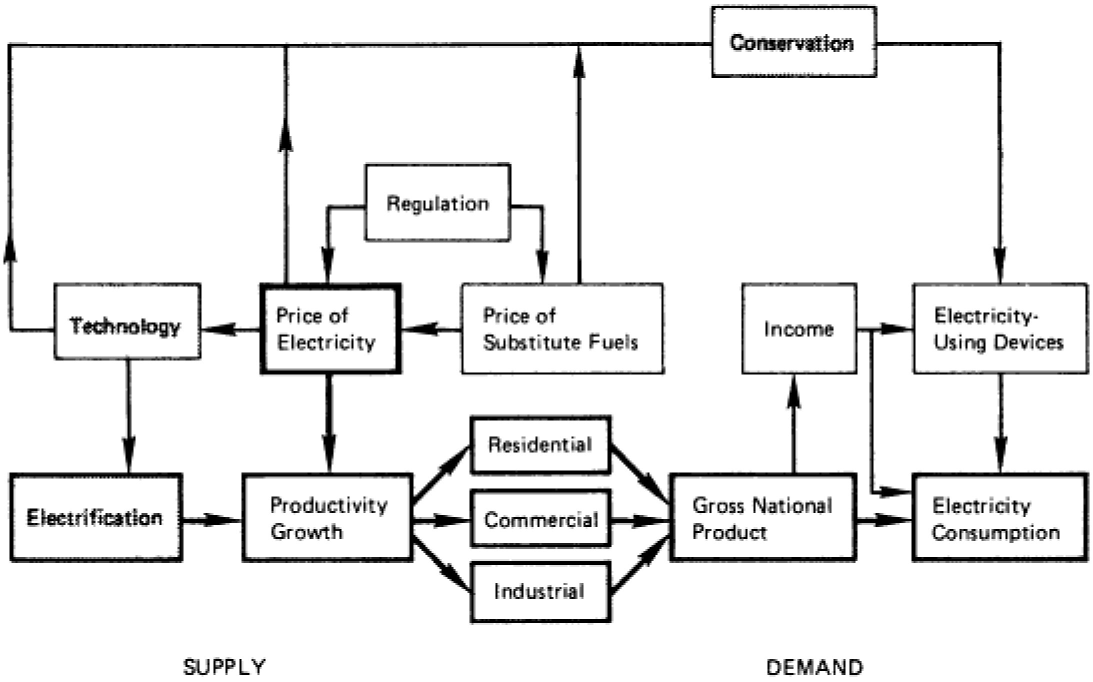
4

Examples of Electrification and Productivity Gains



In the preceding chapter the past relationships between electricity and productivity growth were examined econometrically to understand better the ways technical change and electricity use affect our economy. In this chapter we give some examples of gains in the efficiency of production through particular technical change, that is, through electrification. The discussion bears on the shaded portions of the above reproduction of Figure 1-1. Although considering individual examples about specific users and processes may be illuminating, their aggregate effect is hard to predict. Even so, some general observations about past industrial technological advances, and the role of electricity in them, suggest that electricity is an important energy form in making technological progress.

The examples illustrate the general point that advanced electrotechnologies applied to a particular process often save electricity and other inputs per unit of output. Less quantifiable, but equally important, is the fact that resulting lower costs and higher quality can expand the market, thus increasing total electricity input. Furthermore, in the next 10 to 20 years current processes will incorporate new variations in technique and new products, the competitiveness of which may depend on the new production techniques. The flexibility of electricity will support such innovative processes. Finally, the examples will call to mind other applications, such as the reduction of aluminum ore, that are essentially impractical by nonelectrical means.

The material in this chapter bears on two of the principal conclusions of the study:

- Technical change has made possible many new opportunities for exploiting the special qualities of electricity. In the past these changes were often associated with increased intensity of electricity use, but in the future their net effect on that intensity will depend on the balance between their increased penetration and the increased efficiency of these applications.
- There is further potential for increasing the efficiency of electricity use, particularly in the residential and commercial sectors.

ELECTRICITY AND TECHNOLOGICAL PROGRESS

The attractiveness of electricity as an energy form, as it is associated with advances in production technology and with information and control technology that may not be directly involved in production, arises from two of its significant characteristics. The most important is that electrical energy is a highly ordered form of energy: in the language of physics, its entropy is low. Thus, electricity is applicable quite efficiently to a wide variety of conversion processes. The other attractive characteristic of electricity is that its final form is relatively "clean." In particular, throughout the world electrical energy is distributed at one of two common frequencies and at a few easily changed voltages. Electrical equipment can therefore be reliably and cheaply engineered with the confidence that expensive adaptations will not be necessary to accommodate supply pecularities or waste products at the point of use.

The most obvious use of electricity in many industries is in heating. The advantages of electrical over fossil fuel heating extend beyond environmental concerns. The main benefit is the flexibility with which electrical energy can be delivered, controlled, and tailored to optimal locations in space, to temperatures or energy levels for desired processing chemistry, and to the limitations of the materials used in that processing. Generally, such applications represent a substitution of electrical energy for other energy forms, sometimes with an increase in the efficiency of total energy use.

Any generalization about the implications of advanced technologies for increased electricity use is somewhat uncertain. This uncertainty arises because many of the newer processes carried out by advanced technologies require less electrical energy than the processes they displace. Concentrating heat at the deposition site—using induction heating, microwave heating, or electron beam welding, for example—is one general case of using the special properties of electricity to drive novel process technologies. In the sense of electrical energy required per unit of output, many of these technologies are less electricity-intensive than, for example, resistance heating or arc welding. In short, there are clear examples of enhancing productive efficiency while using less electrical energy. Still, the enhanced efficiency may improve competitiveness and market penetration so that total consumption increases.

Again, although the efficiency of individual electricity-using technologies can be analyzed, predicting the mix of technologies to be expected in the future will at best be incomplete and at worst, wrong. While one can anticipate the decline of some currently employed technical processes, forecasting their future replacements is quite uncertain. Even so, it is instructive to consider some of the diverse forms of electrification that may accompany technical change.

KINDS OF TECHNICAL CHANGE THAT ALTER ELECTRICITY USE

Technical changes that alter electricity use may be classified by how they displace energy to achieve economic gain. The categories selected here represent typical applications of electricity in current use. It is hard to make an exhaustive survey of such processes. Thus, we focus on a few broad, qualitatively different classes:

- Technical changes in which processes using electricity as the primary energy form displace traditional processes that depend on fossil fuel heat, mechanical energy distribution systems, or human labor. Generally such processes are the earliest advantageous industrial applications of electricity, and the resulting rise in productivity is generally accompanied by a rise in the use of electrical energy. Choice of these processes may be encouraged by increasingly attractive prices of electricity relative to those of oil and gas.
- Technical changes in which advanced electrotechnologies displace older electrotechnologies and provide more efficient matching of energy availability to need, resulting in a decrease in energy consumption per

unit of output and often a rise in productivity with respect to other inputs as well. These new technologies may have many of the following attributes: high energy efficiencies; less product waste; better precision and control in the attainment of technical objectives; reduction of the time necessary to attain process objectives; less severe environmental impacts; reduced labor and maintenance requirements; better reliability and quality assurance; and overall economic advantages.

- Technical changes in which additional capital investment in equipment and structures displaces some operating energy requirements. Many conservation techniques represent this kind of substitution, motivated by changing prices and the availability of new conservation technologies and of information about such applications.
- Technical changes in which the enhanced productivity and quality of output that depend on electricity are qualitatively clear, but are not yet easily classified by the direction of energy displacement. Many such applications, including computers, lasers, plasmas, and electrophoresis, are impractical or unachievable by nonelectrical means.

Of course, these general classes describe only roughly any given application. In particular, numerous modern applications for saving energy in heating and cooling buildings depend not only on the availability of the advanced technology, but also on the commitment of a larger initial investment than if the technology were not adopted. In such cases, productivity growth depends both on technical change and on capital substitution. All these categories of technical change tend toward higher productivity in the general economy through increases in productive efficiency in individual firms. The second and third classes of change described above can be expected to show decreased electricity use per unit of output.

The four categories above by no means embrace the wide range of electrical applications, nor are they necessarily the most important for systematic evaluation. They do, however, provide insights into the ways technical changes in using electricity may increase productivity and change energy consumption. An example of each category is given below.

EXAMPLES OF ELECTRICITY-DEPENDENT TECHNICAL CHANGE

Arc Furnace Steelmaking

Arc furnace steelmaking is an example of the substitution of electrical energy for more traditional energy forms, where extensive changes also occur in other aspects of production. These changes encompass not only the energy form used, but also the selection of raw feed materials, the ways specific production can be tailored to the needs of individual users, and, perhaps most importantly, the decentralization of plant locations.

The production of molten steel from scrap in an electric arc furnace is the primary competitor to the conventional blast furnace-basic oxygen furnace (BF-BOF) steelmaking process (Burwell and Devine, 1984). Figure 4-1 illustrates these two processes. In conventional steelmaking, iron ore must be pelletized and introduced into a blast furnace with limestone and coke to produce molten iron. The iron is further processed in a basic oxygen furnace with pure oxygen and other chemical additives to produce steel. Open hearth furnaces, traditionally used to produce steel until the 1950s, have by now been almost completely displaced by the BOF in the United States. In the electric furnace, steel scrap is melted directly with a high-intensity arc. The desired steel composition is controlled primarily by adjusting the composition of the scrap charge, though some refining also takes place in the furnace. Although virtually all of this steel produced in the United States today is made from scrap, electric furnaces can also melt direct-reduced iron generated from ore. This process may become significant over the next decade as scrap supplies are depleted.

Scrap can be used only in limited quantities as an added constituent in BF-BOF steelmaking; combustion heat sources are not intense enough to permit melting scrap economically. As pointed out earlier, however, extremely high temperatures are attainable with electric arc heating; and it is this characteristic that has made electric furnace steelmaking relatively economical. Table 4-1 compares typical production costs for the two processes. Although scrap is more expensive than the feedstocks for the BF-BOF process, other costs, notably of energy and capital, are significantly lower for the electric arc furnace. Table 4-2 compares the primary energy requirements for the two steelmaking processes. The electric furnace process requires about one-third the primary energy (fuel to the power plant) as the BF-BOF process.

Capital costs of BF mills are typically about $450 per annual ton of capacity, compared with about $100 per annual ton of capacity for an electric furnace mill. Furthermore, integrated mills must be sized to take advantage of optimal economy of scale because of the requirements for large ore-handling, coke-making, and pollution abatement facilities. In the United States, the average plant capacity of BF mills is somewhat over 3 million tons per year and that of electric furnace mills is under 0.5 million tons per year. The economic viability of small electric "minimills" close to particular markets has introduced decentralization to the steel industry. Integrated mills are located in only 15 states, with 75 percent of their capacity concentrated in the eastern Ohio-western Pennsylvania and the Chicago areas. Electric mills are located in 32 states, with no more than about 25 percent of their capacity concentrated in any one narrow geographical region.

The relative profitability of arc furnace steelmaking is now accepted as axiomatic in the industry. The fact has been demonstrated especially during times of economic decline. In such times electric mills have generally fared much better than BF-BOF mills, partly

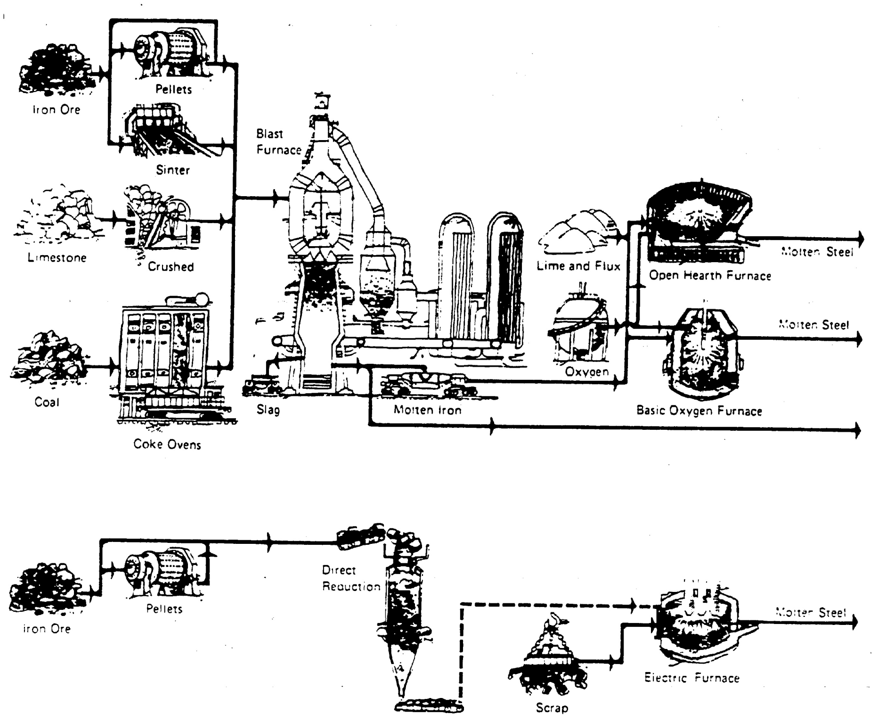


Figure 4-1
Comparison of steelmaking processes: (a) integrated blast furnace, (b) electric furnace.
Source: Schmidt (1984).

TABLE 4-1 Comparative Costs for Producing Molten Steel (1982 Dollars per Ton)

Cost Element	Blast Furnace-Basic Oxygen Furnace	Scrap-Electric Furnace
Raw material	92.40	117.25
Energy (coke @ $150/ton, electricity @ $0.045/kWh)	63.80	21.00
Interest on capital	33.00	12.25
Labor	8.80	7.00
Maintenance and overhead	22.00	17.50
Total	220.00	175.00

SOURCE: Adapted from Schmidt (1984).

TABLE 4-2 Primary Energy Requirements for Molten Steel

Process	Primary Energy (10^6 Btu/net ton)
Blast furnace-basic oxygen furnace	21.1
Coke ovens and blast furnace	19.5
Basic oxygen furnace steelmaking	1.6
Scrap-electric furnace	7.4

SOURCE: Adapted from Schmidt (1984).

because the price of scrap is likely to be low and partly because of the inherent operational flexibility of electric furnaces. The flexibility in output batch size, feedstock, and product specifications yields better deliverability, and therefore better coupling to market needs, resulting in better market penetration. The ability of minimills to produce customized output on relatively short schedules provides a market advantage in many applications that overcomes lower unit costs of offshore steel. Integrating customized production with computer-assisted design and computer-assisted manufacturing in the future should further increase the competitiveness of such producers relative to that of the producers of bulk steel. These observations have led to projecting significant growth in electric steelmaking during the rest of the century, even though only modest growth in overall steelmaking capacity is anticipated. In 1978, U.S. electric furnaces produced 33 million tons of steel, about one-fourth the total. The American Iron and Steel Institute has predicted that the U.S. figure could exceed 50 million tons in 1988, about one-third the total. A U.S. capacity of about 70 million tons has been projected for the year 2000. These figures should be interpreted cautiously: they are based on hypothetical scenarios of overall demand and use of production capacity. The figures are noted here simply to indicate the clear relative economy of the electric furnace process.

Metals Processing by Lasers and Electron Beams

Processing metals with lasers and electron beams exemplifies the displacement of older electrotechnologies by more advanced ones. Some of these new techniques constitute extraordinary advances in performing basic cutting and welding operations in metals. Before, electrification in the form of power drives for saws and electric arc welding was the standard technology. Introducing the advanced technologies significantly enhances productivity and reduces electrical energy use per unit of product. Laser and electron beam processing both have broad applications, including cutting, welding, drilling, and heat treating. They also affect industries ranging from aircraft and automobiles to home appliances and electronics.

Many kinds of metal fabrication are labor-intensive, so processing speed and number of operations are critical to overall production economy. Although it has been shown, in fact, that laser and electron beam processes often conserve energy compared with conventional metal cutting and welding processes, this discussion focuses primarily on labor-related parameters.

Laser Processing

The high energy deposition rates of lasers and their ability to control the energy source precisely in location, direction, time, and intensity together give rise to the productivity advantages illustrated here.

For example, circular saw blade blanks can be laser cut to customized specifications, providing shorter delivery times and better quality than conventional stamping processes.

Table 4-3 compares typical laser cutting speeds with those of conventional mechanical saws for steel and titanium plates of varying thicknesses. Titanium presents a particularly difficult sawing operation because of its high hardness. Hardness is essentially irrelevant in laser cutting, since the laser beam simply vaporizes the metal. As a result, cutting speeds with the laser are roughly 25 times faster than with sawing. For working steel, which is not as hard as titanium, a speed advantage of 5 to 10 times is still achievable.

Table 4-4 shows the resulting labor savings for a typical application—cutting complex titanium shapes in manufacturing high-performance aircraft. These figures include setup and postprocessing time as well as actual cutting time. Employee-hour savings of 60 to 65 percent are typical with the laser process. Overall cutting costs for this application are shown in Table 4-5. Cost savings for the laser process range from about $1 to $3 per foot, depending on material thickness. The capital cost of the laser system, however, is significantly higher. This cost premium would typically be recovered in producing about 2,000 parts of 1/2-in. thickness and of 20-ft perimeter (structural elements, for example) or about 5,000 or 6,000 parts of 1/8-in. thickness when the perimeter is similar (for example, fuselage skin panels).

Electron Beam Processing

The primary application of electron beams today is in welding thick steel and aluminum sections, for example, in the automotive and shipbuilding industries. Electron beams with velocities approaching the speed of light have tremendous penetrating power and can be magnetically focused to an area about 1 mm^2. Plates ranging from 1/2 to 6 in. in thickness can be welded in a single pass with an electron beam while conventional arc or oxyacetylene welding techniques require 2 to 20 passes. The intensity and focusability of electron beam welders provide indirect as well as direct processing speed advantages. Figure 4-2a illustrates that the heat-affected zone in a conventional multipass weld varies from almost zero at the bottom of the weld to approximately the plate thickness at the top. By comparison, the electron beam weld is almost uniform in width throughout the plate and results in a relatively small heat-affected zone (typically the thickness of a pencil). This feature results in high weld integrity and low transverse shrinkage; uneven shrinkage in conventional welding distorts the plate as shown in Figure 4-2b, requiring postprocessing heat treatments to correct that distortion. Residual stress remains as a failure-promoting attribute even after stress relief of conventional welds.

TABLE 4-3 The Comparative Cutting Speeds of Lasers and Saws

		Average Cutting Speed (in./min) for Different Thicknesses		
Material	Process	1/50 in.	1/16 in.	1/8 in.
Titanium	Saw	8.5	5.8	4.4
	Laser	200	160	120
Steel	Saw	8.5	5.8	4.4
	Laser	80	40	20

SOURCE: Schmidt (1984).

TABLE 4-4 Comparative Labor Costs for Cutting Titanium Aircraft Components (Including Setup and Postprocessing Time), with Band Sawing and Laser Cutting Techniques

Component Type	Band Sawing (man-min/ft)	Laser Cutting (man-min/ft)	Savings (percent)
Large contoured skin panels	10.4	3.65	65
Ribs and longerons	6.0	2.32	61
Small skin panels	6.25	2.38	62

SOURCE: Adapted from Schmidt (1984).

TABLE 4-5 Titanium Cutting Cost Comparisons (in 1982 Dollars)

		Total Cost (dollars/ft)[a]		
		Material Thickness		
Cutting Process	Capital Investment (dollars)	1/8 in.	1/4 in.	1/2 in.
Saw	2,000	1.52	2.18	4.15
Laser	96,000	0.71	1.19	1.28

[a] Includes operating and secondary finishing costs. SOURCE: Adapted from Schmidt (1984).

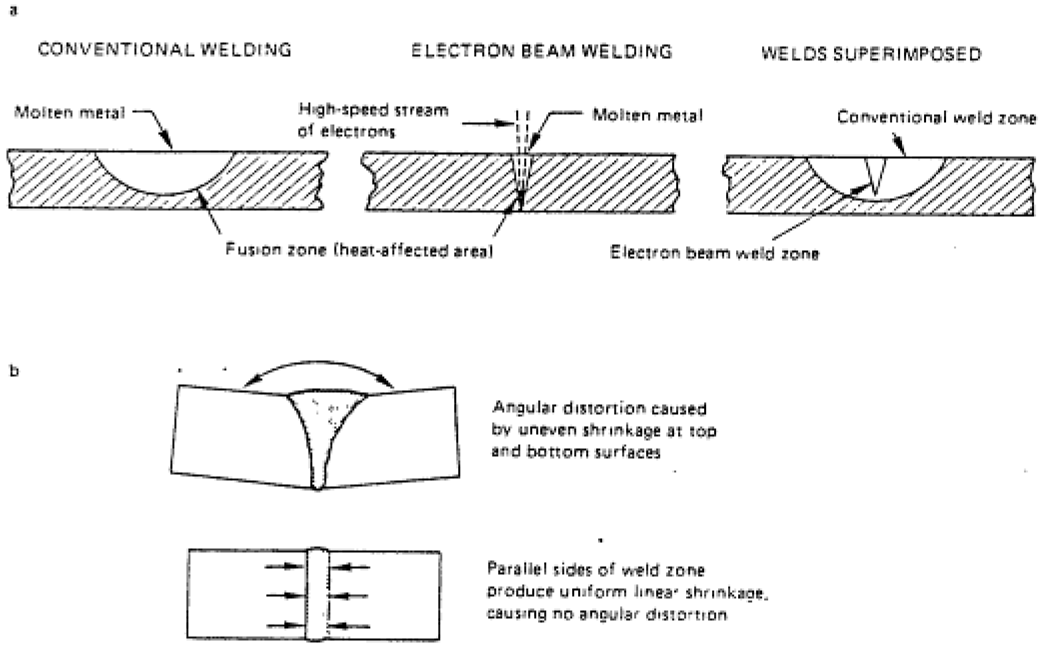


Figure 4-2
(a) Comparison of heat-affected zones for conventional and electron beam welding, (b) distortion of parts from shrinkage. The lower residual stresses in the parallel weld minimize regions susceptible to cracking and failure.
Source: Schmidt (1984).

Table 4-6 shows the overall speed and cost advantages of electron beam welding over conventional inert-gas arc welding. Although energy use is not the primary factor in welding production costs, the electron beam process is extremely energy-efficient, typically requiring less than one-tenth the energy of arc welding. More significantly, complete welding time, including setup and postprocessing, is typically reduced by the electron beam processing by about five times. The resulting cost differentials per inch of weld range from 400 to 450 percent. As in using lasers, however, the initial investment in electron beam equipment is high; thus the process is best suited to high-production applications, such as welding automobile bodies and chassis components.

Investments in Energy Efficiency of Buildings

Capital investment in a wide variety of passive or active energy conservation systems can reduce the energy requirements necessary for acceptable environments in commercial buildings and residences. Many of these measures are equally relevant to electric and nonelectric means of space conditioning. However, to the extent that such investments affect electricity use for heating, ventilation, air conditioning, and lighting, they exemplify the third category of technical change described above. The following approaches are among those already well known and practiced:

- Using insulation, double glazing, and tinted and reflected glazings
- Using heat pumps and other more efficient heating, ventilation, and air-conditioning equipment
- Using advanced lighting technologies
- Using energy storage systems to reduce peak demand
- Improving controls for more efficient energy management
- Improving building design.

Some of these features can be retrofitted, but with less effect on energy use. Applying these techniques in new construction, however, can provide dramatic annual reductions in total energy requirements.

The potential of implementing such measures is captured in Figure 4-3, which presents past trends and future possibilities in the energy intensities of office buildings. Energy use in typical new commercial buildings is estimated to have risen from about 300 thousand British thermal units per square foot per year (kBtu/ft^2-year) in 1952 to about 480 kBtu/ft^2-year in 1975. The U.S. office building stock in 1960 is estimated to have used about 350 kBtu/ft^2-year. Evolving standards suggest that lower office building resource energy intensities are attainable in new construction, for example, about 100 kBtu/ft^2-year in the early 1980s. A still lower value of about 70 kBtu/ft^2-year for new construction is seen for 1990, presuming such operations are economical. Average office building resource energy intensity for the existing stock will gradually fall as a result of the

TABLE 4-6 Comparison of Electron Beam (EB) and Metal Inert Gas (MIG) Welding

	Maraging Steel (1-in. Thickness)		Titanium (1-in. Thickness)	
Feature	EB	MIG	EB	MIG
Number of passes	1	10	1	10
Welding speed (in./min/pass)	40	10	15	20
Total welding time (min/ft)	0.3	12	0.8	6
Total setup, weld, and clean time, typical job (min)	49	280	55	243
Relative cost (operating and labor)	1.0	4.1	1.0	4.5

SOURCE: Schmidt (1983).

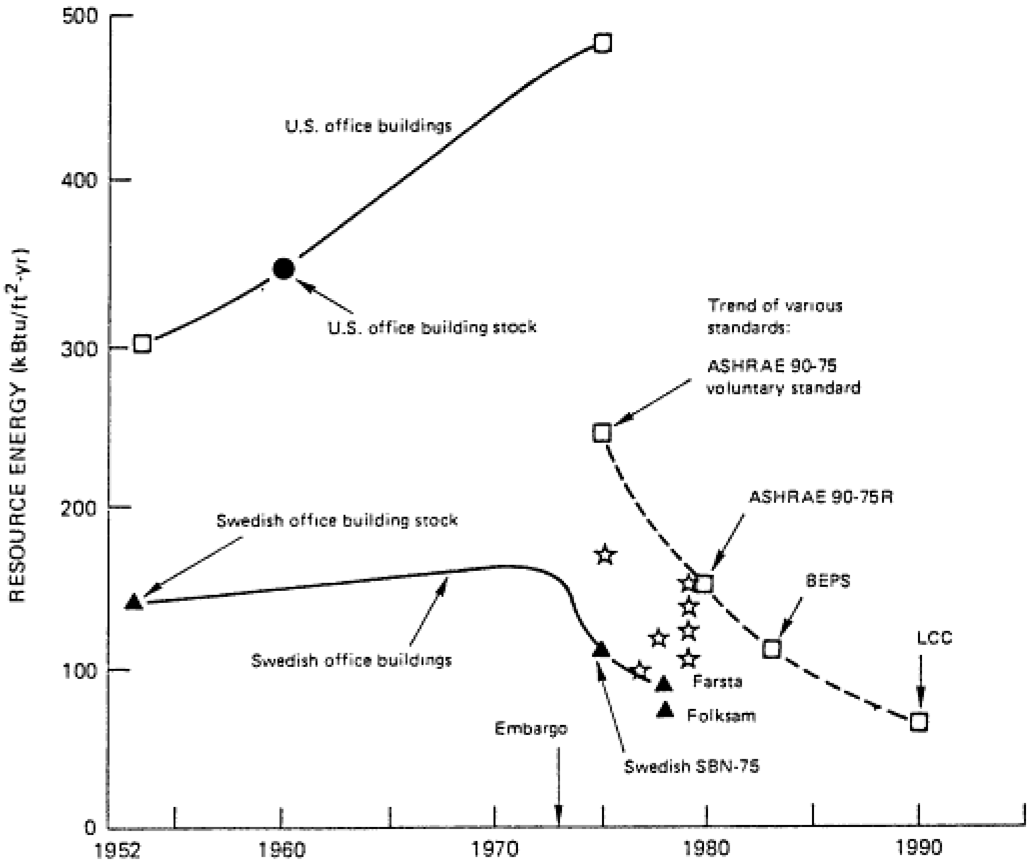


Figure 4-3
Office building resource energy intensity, 40-year trends.
Note: Trends in annual energy use per unit floor area per year of new U.S. and Swedish office buildings. Seven recent energy-efficient office buildings are represented by "*". ASHRAE, American Society for Heating, Refrigerating, and Air-Conditioning Engineers; BEPS, Building Energy Performance Standards; LCC, life cycle cost. Electricity is counted in resource energy units at 11,500 Btu per kWh.
Source: Adapted from Kelly and Gawell (1981).

improved standards for new construction, but the average will lag the standard because of the slow pace of stock turnover and retrofit.

Efficient lighting and energy storage are of particular interest for energy conservation in buildings. Lighting in commercial buildings contributes a significant fraction of the air-conditioning load and also contributes to a reduction in heating load during cold weather. Potential improvements are attainable in at least two ways. Improved designs that allow for more daylighting will cut lighting heat loads from a typical value of 1.5 watts per square foot (W/ft^2) to the lower value of 1 W/ft^2. With new technologies for highly efficient lighting, the typical fluorescent lamp (80 lumens/W) may lead to to more advanced types of lighting:

- Isotopically enhanced lamps (110 lumens/W) by 1985
- Magnetically loaded lamps (135 lumens/W), by 1990
- Two-photon phosphor lamps (200 lumens/W), by 1995.

The technology and applications of energy storage for cooling have gained significant popularity. Their main contribution is through reducing peak loads. In addition, since cooling storage takes place at night at relatively lower ambient temperatures, energy can be saved because of the resulting higher efficiencies of the heating, ventilating, and air-conditioning system. Typical storage media include chilled water and ice. Phase-change polyalcohols are being researched and may be used. All these methods require separate storage facilities, which pose a special challenge in retrofitting buildings. In new buildings, the thermodeck hollow-core floor slab integrates heating and cooling storage into the structure of the building. This design requires no visible structure for storage. Many such applications are only marginally productive, and their effectiveness must be determined by analysis of the specific situation. However, penetration of storage-augmented systems is increasing.

Automation

Automation is an example of technical change involving electricity where the promise of enhanced productivity is already clear but the impact on ultimate energy use is not. Such applications of electricity have a direct bearing on efficiently using time, space, capital, labor, energy, and materials, particularly in the commercial and industrial sectors. However, corresponding biases of productivity growth, as discussed in Chapter 3, are not yet established. We have not yet measured whether automation is capital using, electricity using, labor saving, materials saving, or anything else.

Computer-aided technical analyses, communications systems, miniaturization of office equipment, and electronic storage of data are some applications now receiving wide attention. Nevertheless, the full range of applications cannot be foreseen at this time. In addition to end-use applications, growth in the use of automation equipment will positively affect the economy by encouraging the growth and development of new industries.

In manufacturing, terminal equipment is used for data entry and data access. Mainframe computers manage data bases and electronic messages and perform scientific and engineering calculations. The more effective handling of information is essential to optimizing overall productivity of a firm or an economic sector. Automated information systems can effectively match and synchronize the flow of materials, equipment, designs, labor market, and delivery data, for example.

In retail trade, the primary application is point-of-sale terminals tied to minicomputers. This use not only simplifies individual transactions but also introduces real-time inventory control, thereby reducing invested capital.

In education, electronic tools are also becoming widespread. Elementary and secondary schools increasingly are making microcomputers available to students, together with courses in their use. Colleges and universities are integrating computers into their curricula.

Although this discussion focuses on automation in the commercial and industrial sectors, there will probably be significant use of microcomputers and videotext equipment in individual residences also.

Few data are available to estimate the potential relationship between office automation and electricity use. The Electric Power Research Institute (EPRI) has attempted to quantify this relationship (Roach, 1985). Table 4-7 lists various types of electronic equipment and their typical power requirements. These values have been used in the preliminary estimate of electricity use discussed below.

Roach assumed that 3.5 million terminals and 13,000 mainframe computers would be installed in offices in the manufacturing sector. Point-of-sale terminals would be installed at all stores with five or more employees, store growth would be 34 percent by the early 1990s, and 43 percent of the terminals would replace electronic cash registers in the retail sector. Each college student and one in five elementary and high school students would have microcomputers. All homes with incomes of greater than $25,000 would install a microcomputer.

The capacity required, based on these assumptions, is about 30,000 MW. The electric energy requirement, similarly, is about 100,000,000 MWh per year. Such calculations are of course preliminary. In addition, how much other energy-using technology may be displaced is not well understood. EPRI is continuing the study of electricity use and will extend it to include the many nonmanufacturing offices, health care facilities, and financial institutions.

However, the impact of using such equipment on productivity and efficiency is not really measured by the electricity consumption of office machines and computers. Rather, the proper measure is the improved handling of information to make the most efficient and coordinated use of production facilities, labor, and materials. To take a single example, the inventory control for replacement parts for computers is itself a large, though largely invisible, industry. Without this kind of system, the worldwide penetration of U.S.-made

TABLE 4-7 Estimated Power Requirements for Electronic Office Equipment

Technology	Brand	Features	Power Requirement (watts)
Microcomputer	IBM PC	512-kilobyte memory, two disk drives, monochrome screen, dot-matrix printer	340
Microcomputer	IBM PC/XT	512-kilobyte memory, 10-megabyte hard disk drive, color screen, dot-matrix printer	614
Microcomputer	Apple Macintosh	128-kilobyte memory, one disk drive, screen	60
Microcomputer	AT&T	System unit only	230
Minicomputer	IBM System 38/Model 8	Up to 8 million characters of memory, IBM 3370 for storage, IBM 3262 for printing, tape drive, and five terminals	8,500
Minicomputer	DEC VAX 11/750	DEC RA81 for storage, LP06 for printing, and five LA120 terminals	7,310
Minicomputer	DEC VAX 11/780	Up to 4 megawords of memory, DEC RA81 for storage, LP06 for printing, and five LA120 terminals	9,110
Mainframe	IBM 3084	Up to 96 million characters of memory, IBM 4248 printer, IBM 3380 for disk storage	22,800-31,300
Computer terminal	IBM 3279	With mainframe	300
Computer terminal	IBM	With system 38	200
POS terminal[a]	IBM 365		320
POS terminal	NCR 280		400
POS terminal	IBM 3684		360
Large video screen	RCA PJR	50-in. screen	235
Video cassette recorder	RCA		300
Microfiche reader and printer	Minolta RP401e		250
Phone recorder	Panasonic		20

[a] POS: Point-of-sale.

SOURCE: Roach (1985).

computers would be impractical, since the parts availability and replacement channels would become much more costly and much less responsive to need.

A full discussion of automation in the industrial sector is not necessary for the purposes of this section. However, the technology should at least be cited as a primary tool for higher process efficiency, higher quality, and the conduct of operations not practical by manual means. Essentially all advances in automation depend on electrical sensors, actuators, and computerized control systems. There are already products, such as automobile bodies, for which the market share of nonautomated production is rapidy declining. For these products, automation is perceived as the most practical route to consistently high quality and thus competitiveness.

OTHER INDUSTRIAL TECHNOLOGIES

Many other examples of electricity-dependent change, particularly in the industrial sector, are pertinent. They range from plasma processes for metals reduction, melting, and chemical processing through electroytic processes for separating and refining metals and chemicals to infrared and ultraviolet radiation curing. More complete lists of industrial opportunities are given in Table 4-8 and Table D-1 of Appendix D. Examples drawn from commercial, residential, and transportation sectors are given in Tables D-2, D-3, and D-4, respectively, of Appendix D.

THE SIGNIFICANCE OF ELECTRIFICATION

As noted at the beginning of this chapter, its purpose has been to describe some of the technologies that will shape the future relationship between electrification and gains in production efficiency. More specifically, various new electrotechnologies promise to increase national productivity through new applications of electricity. Chapter 3 showed that the relationship of electricity to sectoral production is dual: (1) for many industries technical change is electricity using in the sense that it increases the share, relative to those of other inputs to production, that a given change in electricity input value contributes to change in output value and (2) for the same industries a drop in the price of electricity, in association with technical change, increases their productivity growth.

The examples here allow us to conclude that electricity has unique properties that make it an attractive form of energy, namely:

- Constituting a highly organized form of energy, virtually completely convertible into other forms, such as motion, heat, light, or chemical potential

TABLE 4-8 Industrial Electrotechnologies and Their Applications

Technology	Major Applications
Arc furnace steelmaking	Wide range of steelmaking processes
Plasma-based metals reduction	Extractive metallurgy and ferrous metals processing
Plasma-arc production of chemicals	Production of acetylene and ethylene, use of coal to produce basic chemicals, etc.
High-temperature electrolytic reduction	Improving productivity in producing aluminum and magnesium
Induction melting	Improving productivity in many varied applications in metals production
Plasma melting, cutting, and spraying	Large-scale melting of basic metals
Induction heating	Forging industry and potential large-scale applications
Electroslag remelting and casting	Production of high-alloy ingots of simple geometry and potentially those of complex geometry
Laser materials processing	Metal cutting, drilling, welding, and heat treating
Electron beam heating	Welding and heat treating in automotive, shipbuilding, and related industries
Other high-temperature technologies (resistance melting, resistance heating, vacuum melting, homopolar pulsed heating, etc.)	Materials production and fabrication
Heat pumps and mechanical vapor recompression	High-temperature heat recovery (e.g., in pulp and paper industries), distillation, and drying
Electrolytic separation and electrochemical synthesis	Production of inorganic chemicals, water treatment, trace metal removal, etc.
Dielectric heating with microwaves and highfrequency radiation	Food processing and drying applications
Ultraviolet and electron beam radiation curing	Improving productivity in the coatings industries
Other medium- and low-temperature technologies	Surface coatings, various industrial operations, uranium separation, etc.

SOURCE: Adapted from Schmidt (1984).

- Permitting previously unattainable precision, control, and speed
- Providing temperatures greater than those available using fossil fuels
- Flexibly operating process equipment on power generated from many fuels
- Leading to few, if any, waste products and environmental hazards at its point of use, compared with fossil fuels
- Requiring no inventory.

These properties of electricity underscore its importance as an energy source in high-technology, information-based activities.

Electrification is also an industrial process that can change not only the form of energy used but also the amount and kind of labor, capital, and materials inputs; product quality; and the location of manufacture. These changes may result in increased efficiency of production, in the form of equivalent output at lower input cost, and hence, lower prices.

The foregoing examples illustrate the strong relationship between technological improvements, the use of electricity, and increases in the efficiency of production. The question remains whether this relationship will continue, and what its net effect will be on electricity consumption. This is the subject of Chapter 5.

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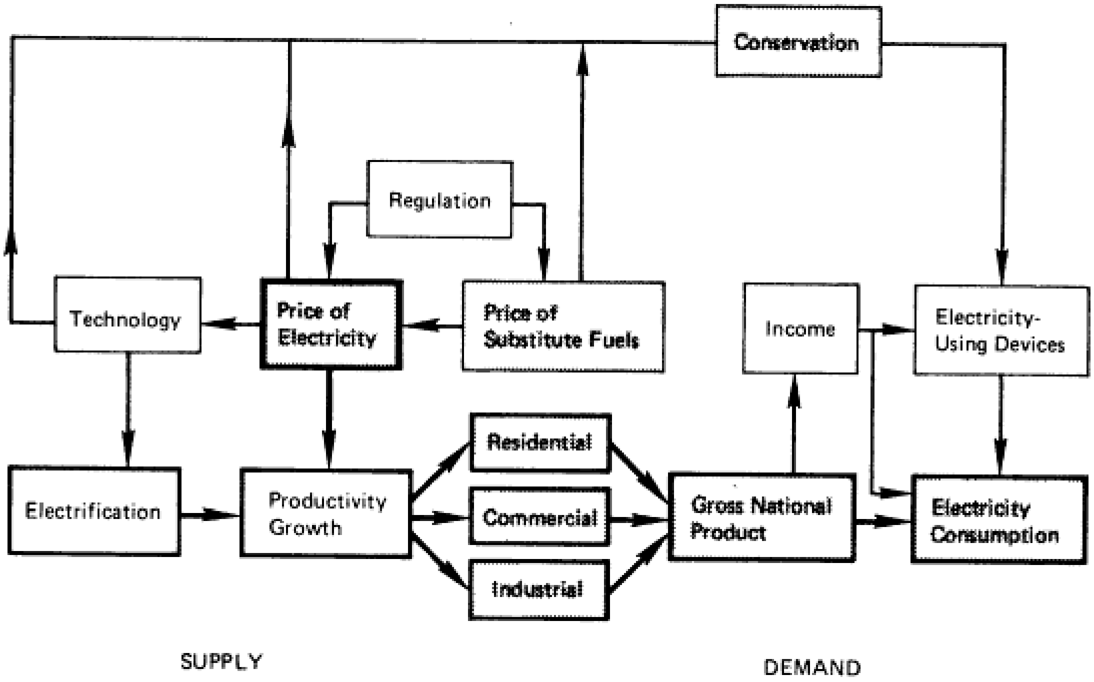
5

Future Economic Influences on Electricity Use



This chapter considers some potential economic influences on electricity use in the future. The shaded portions of the above reproduction of Figure 1-1 identify the areas of discussion. The principal questions that the chapter takes up are these: (1) what major factors are likely to influence future electricity consumption patterns relative to gross national product (GNP) and (2) how significant might their influence be on electricity demand? An ancillary issue is the relationship between energy prices and productivity growth rate, treated in Chapter 3, since productivity growth affects GNP, which in turn affects electricity use.

A number of the historical patterns of electricity use analyzed in Chapter 2 may persist. First, there has been a remarkably stable linear relationship between electricity consumption and GNP. In particular, incremental electricity intensity has demonstrated long periods of stability, with major increases following World Wars I and II (see Figure 2.2). Since World War II the percentage growth rate of electricity consumption has declined and so has its magnitude relative to percentage growth rates of gross economic output (Figure 2.5) and outputs of the major individual sectors (Figure 2.7). Specifically, since the war the percentage growth rate of electricity consumption, formerly several times greater than that of GNP, diminished, and in the last few years its value has approached the latter. Since the Arab oil embargo of 1973, the ratio of percentage growth rate of electricity consumption to that of GNP has been near unity.

As discussed in Chapter 2, although this recent trend is consistent in principle with the observed linear relationship between electricity consumption and GNP, the question remains whether the degree and rate of convergence of the growth rates are consistent with the long-term trend that has characterized the postwar period. Chapter 2 also left open the question whether the recent relationship between electricity use and GNP represents a permanent change in slope of the long-standing linear relationship between the variables, whether it is part of a cycle that has persistently characterized the long-term relationship, or whether it is a permanent one-time shift in the intercept of the established linear relationship.

In this chapter we go further, examining the important forces that have shaped the historical picture. Several generalizations can first be made: (1) the level of economic activity will continue to be the most important determinant of future electricity use and (2) great uncertainty arises in estimating the quantitative outcome of the interactions among the other important determinants of electricity use. This uncertainty is in large part traceable to the difficulty in forecasting future values of the determinants in question. Nonetheless, we can take stock of some of the factors capable of perturbing the simple linear relationship between electricity use and GNP. We can consider how they might qualitatively influence the future relationship between electricity use and certain economic measures.

First we review several recent forecasts of average annual growth rates of electricity consumption and GNP to illustrate their disparity. This background material is followed by discussions of the changing composition of national output, the likely effects of electricity and alternative fuel price movements, conservation practices and potentials that might affect electricity consumption patterns, and a few observations about how the factors may affect the outlook for electricity use.

The material here, along with related material in other chapters, helps to support two of the principal conclusions of the report:

- Valid conclusions about electricity demand drawn from national data do not necessarily pertain to regional circumstances; there are significant regional differences in such factors as economic output, prices, electricity supply mix, availability of capacity, climate, and regulatory environment.
- Electricity prices and alternative fuel prices affect electricity consumption in two ways: first, they directly affect the use of electricity and nonelectric fuels as factors of production; second, they indirectly affect productivity growth and thereby economic growth.

THE RANGE OF RECENT FORECASTS

The Edison Electric Institute (1984) reviewed and compared a number of recent relative growth rate projections for electricity consumption and GNP. The results are reproduced in Table 5-1.

The rows correspond to the various forecasts, with each forecast period noted in parentheses. The rightmost column presents the ratio of the growth rates of electricity consumption and GNP for the forecast period. The other columns present the forecasts for intermediate variables, provided that they were available from the original source. The first data column gives the projected average annual real GNP growth rate, the second the projected average annual change in the price of imported oil, the third the projected average annual growth rate of primary energy use, the fourth the projected growth rate of energy consumed at the point of end use, the fifth the projected growth rate of electrical energy use, and the sixth the corresponding growth rate of peak demand for electricity.

The electricity-to-GNP ratios range widely, from -0.32 to 1.29, in the studies reviewed. These values correspond to forecasts in which the real GNP growth rates range from 2.5 to 3.5 percent per year, and in which electricity consumption growth rates range from -0.8 to 4.5 percent per year. Even though these forecasts were prepared using quite different methods and assumptions about economic growth and world oil price prospects, such a wide range of electricity-to-GNP ratios is surprising. Yet even this range is narrower than it has been at earlier times. The authors state (Edison Electric Institute, 1984, p. ii):

> The range of projected growth rates has narrowed considerably over the past few years. Only 'least cost' studies, such as those of the Audubon Society and Roger Sant's 'Creating Abundance' indicate lower growth rates for energy consumption than the consensus. Siegel and Sillin, the mavericks among the analysts, project both higher economic growth and electricity consumption.

TABLE 5-1 Average Annual Percentage Growth Rates of Selected Indicators and the Ratio of Growth Rates of Electricity Consumption and Gross National Product (GNP)

Forecast Source and Period	Real GNP	Average Oil Import Price	Primary Energy	End Use	Electricity	Peak Demand	Electricity-GNP Ratio
SIEGEL (1983-2000)	3.5	n/a[a]	n/a	n/a	4.5	n/a	1.29
AEO (1983-1995)	2.9	4.6	1.7	1.2	3.3	n/a	1.14
DRI (1983-2000)	2.9	1.9	1.6	1.2	3.1	2.4	1.07
DOE (1982-2000)	2.8	3.0	1.3	0.9	2.8	n/a	1.00
EL.WORLD (1983-2000)	2.9	n/a	n/a	n/a	2.8	2.9	0.97
COM (1983-2000)	2.7	n/a	1.1	0.7	2.5	n/a	0.93
NCA (1982-1995)	2.5	1.8	1.4	1.2	2.3	n/a	0.92
WHARTON (1983-1994)	3.3	0.4	1.9	1.3	3.0	n/a	0.91
GRI (1983-2000)	2.8	1.8	1.6	1.3	2.4	n/a	0.86
CON (1982-2000)	2.8	n/a	1.1	0.8	2.1	n/a	0.75
SANT (1980-2000)	2.6	2-3	0.7	0.5	1.5	n/a	0.58
AUD (1980-2000)	2.5	4.7	-0.4	-0.3	-0.8	n/a	-0.32
NERC (1984-1993)	n/a	n/a	n/a	n/a	2.7	2.5	n/a
BANK (1982-2000)	n/a	n/a	n/a	n/a	2.9	2.5	n/a

NOTES:

AEO: U.S. Energy Information Administration, 1983 Annual Energy Outlook. May 1984.

AUD: National Audubon Society. The Audubon Energy Plan, Conventional Baseline Scenario. July 1984.

BANK: Chemical Bank. U.S. Electric Utility Industry Outlook to the Year 2000. February 1984.

COM: Joseph F. Gustaferro, U.S. Department of Commerce. U.S. Energy for the Rest of the Century. July 1984.

CON: Conoco. World Energy Outlook Through 2000. April 1984.

DOE: U.S. Department of Energy. Energy Projections to the Year 2010 (NEPP IV). October 1983.

DRI: Data Resources Incorporated. Energy Review. Autumn 1984.

EL.WORLD: Electrical World. 35th Annual Electric Utility Industry Forecast. September 1984.

GRI: Gas Research Institute. 1984 GRI Baseline Projection of U.S. Energy Supply and Demand 1983-2000. October 1984.

NCA: National Coal Association. Coal Markets in the Future. March 1984.

NERC: North American Electric Reliability Council. Electric Power Supply and Demand 1984-1993. 1984.

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[a] "n/a": not available.

SOURCE: Edison Electric Institute (1984).

There are significant differences among the forecasts of Table 5-1 in the set of public policies each presumes to be in effect. For example, "the Audubon Energy Plan is a detailed comprehensive program based on energy conservation through more efficient use of fuel, and increased reliance on renewable energy—solar power, wind and water power, and the use of biomass. The plan spells out specific legislative and administrative steps that would have to be taken by the Federal government." In a similar vein the Sant forecast is "'a Least-Cost' case, where all cost effective end use energy investments are made" (Edison Electric Institute, 1984, p. iii). Other forecasts in the table assume a policy and decision-making environment close to that of today.

The foregoing compilation illustrates the substantial differences of opinion about the future relationship between electricity use and GNP. To understand how such differences can arise, we turn to the forces that shape the relationship. We shall see that the estimates diverge mainly because it is hard to quantify and predict rather than because it is assumed that departures will occur from the economic forces that have so far been present.

THE CHANGING COMPOSITION OF NATIONAL OUTPUT

Figure 2-6 illustrated that basically linear relationships have prevailed between electricity use and representative measures of economic activity in each of the three main sectors of the economy. The historical patterns of change in the composition of national output were also reported in Chapter 2 (Tables 2-3 through 2-5). Is there reason to believe that the composition of national output, as it affects sectoral use, will change the relationship between electricity use and GNP in the future? How important will the composition of output be compared to other determinants of electricity use? To facilitate discussion of these questions, we analyze the economy by the three broad sectors discussed in Chapter 2. We find that diverse forces arise from changing the composition of national output and that their net effect is likely to alter electricity consumption in some small and gradual degree.

The trend in composition of national output since 1950 is a relative growth of the services portion, compared to the industrial portion, of the economy. Correspondingly, electricity use in the commercial sector has grown compared to that in the industrial sector, standing at about 28 percent of total use in 1983 (Table 2-2). In addition, residential use of electricity has grown compared to industrial use, the measures standing respectively at about 34 and 38 percent of all use in 1983 (again, see Table 2-2). These differences can be traced to the differences in trends in growth in disposable personal income versus gross product originating (GPO) in the industrial sector.

Electricity is used in industry primarily for motor drive, electrolytic processing, and process heat. Commercially, the principal uses of electricity are for space conditioning and lighting. In the residential sector, major end uses are space conditioning, refrigeration, water heating, lighting, and cooking. Thus, the forces that drive future electricity use related to measures of economic output are different for each sector. We first discuss some prospects for the industrial sector with particular attention to manufacturing. We then consider some prospects for the commercial and residential sectors.

The Industrial Sector

Trends in Electricity Use

The industrial sector used about 38 percent of all electricity consumed in 1983. In considering the future electricity consumption of this sector it is convenient to treat it in two parts--for those industries that are (1) more electricity-intensive and (2) less so, measured by electricity use per unit value of output.

The six most electricity-intensive manufacturing industries of our economy are those of primary metals; paper and paper products; petroleum processing; chemicals; stone, clay, and glass; and textiles. In 1980 these six industries accounted for 68 percent of the electricity consumption in the industrial sector (Resource Dynamics Corporation, 1984). The electricity intensity of these six industries has remained relatively constant for the past three decades (see Figure 2-13). However, the proportion of manufacturing output contributed by these industries has also exhibited a fairly consistent decline (Figure 2-12). The declining share of these industries in GPO has contributed to the relative decline in the electricity intensity of the manufacturing sector.

To project these relationships further requires forecasting the growth prospects of electricity-intensive manufacturing industries relative to those of non-electricity-intensive industries, something the committee did not attempt. A recent study (Data Resources, Inc., 1984), however, did consider some alternative forecasts. In one projection of the compound annual growth rates for 1986 through 1995 for a 400-level Standard Industrial Classification disaggregation of the economy, 3 of the 20 slowest growing activities were textile-related and 4 were petroleum-related. In addition, 4 more of the 20 slowest growing activities were construction-related, industries heavily dependent on metals and stone, clay, and glass products (ibid., Table 1.4). Thus, at least according to this forecast, 11 of 20 of the slowest growing industrial activities belong to the electricity-intensive manufacturing sectors.

It is hard to draw a strong conclusion from only one forecast, premised on a large number of scenario parameters that are not reported here (ibid., pp. 1-27). However, if such trends prevail, they do suggest a continuing slight decline in electricity consumption growth relative to measures of aggregate industrial output growth, provided new technologies do not change the historical trends.

The effects of other manufacturing industries, that is, of non-electricity-intensive ones, on general trends in electricity consumption are more difficult to assess.

Figure 2-13 showed that the intensity of electricity use of the other manufacturing sectors decreased about 15 percent between 1970 and 1981. The reason for this trend, noted in Chapter 2, was that these industries generally are already highly electrified, and thus efficiency improvements have outweighed any incremental penetration of electricity use.

Such gains in efficiency can in part be traced to the use of more efficient electric motors. Table 5-2 illustrates patterns of electricity consumption in the industrial sector in 1980 by industry and end-use application. By far the largest such application was for motor drives. Electric motors, in fact, accounted for about 63 percent of industrial electricity use in that year.

In this regard, one recent report concluded the following (U.S. Congress, Office of Technology Assessment, 1984, p. 37):

> Improvements in the efficiency of electric motors are likely to be continuous for 10 to 15 years through improvements in the motors themselves and through improved efficiency of use which takes advantage of new semiconductor and control technology. Thus, electricity use per unit of output could decrease by 5 percent (if there is little price stimulus). Some of this improved efficiency should come about as a result of past price increases, as capital stock turns over.

The difficulty in coming to such a conclusion is that data are not available on the proportion of electric motors in industry that have already been replaced by newer, more efficient substitutes and those that remain to be replaced. However, to the extent that the non-electricity-intensive industries use motor drive, they may enjoy a continuing modest increase of efficiency of electricity use.

Offsetting the trends mentioned above is the prospect that new electricity-using technologies will tend to increase electricity use in the industrial sector relative to economic output. Table 4-8 gave examples of these technologies, with attention to their applications for productivity growth. In the next section we consider the potential influence of these technologies on future electricity use.

The Growth of Electrified Processes

Will new electrotechnologies significantly influence future electricity use patterns in industry? The report cited above comprehensively reviewed the prospects, stating that "great uncertainty surrounds the contribution to industrial electricity demand from the most important

TABLE 5-2 Electricity Consumption by Industry Sector and End Use, 1980 (Billions of Kilowatt Hours)

		End Use			
SIC and Industry[a]	Total Electricity Consumption	Motor Drive	Electrolytic Processes	Process Heating	Unclassified
PROCESS RELATED					
28 Chemicals and allied products	145.0	96.9	31.7	0.4	16.0
26 Paper and allied products	76.0	61.6			14.4
20 Food and kindred products	43.3	35.1		2.7	5.5
29 Petroleum and coal products	37.7	31.3			6.4
22 Textile mill products	26.1	20.6		0.5	5.0
30 Rubber and miscellaneous plastics	21.9	19.0			2.9
24 Lumber and wood products	14.8	11.0		0.5	3.3
27 Printing and publishing	9.7	7.1			2.6
23 Apparel, textile products	6.0	4.4			1.6
Totals for process-related industries	380.5	287.0	31.7	4.1	57.7
PRIMARY METALS					
33 Primary metal industry	175.4	50.9	71.3	33.2	20.0
FABRICATED METALS					
35 Machinery, except electrical	30.7	20.9	0.1	8.8	0.9
37 Transportation equipment	30.0	22.8		3.2	4.0
36 Electrical equipment	27.2	22.5		0.5	4.2
34 Fabricated metal products	25.3	10.9		13.2	1.2
38 Instruments, related products	6.0	4.2			1.8
39 Miscellaneous manufacturing industries	3.6	2.5			1.1
Totals for fabricated metals industries	122.8	83.8	0.1	25.7	13.2

		End Use			
SIC and Industry	Total Electricity Consumption	Motor Drive	Electrolytic Processes	Process Heating	Unclassified
STONE, CLAY, AND GLASS					
32 Stone, clay, and glass products	30.8	24.7		2.4	3.7
OTHER	7.4	5.4			2.0
TOTAL	716.9	451.8	103.1	65.4	96.6

[a] SIC: Standard Industrial Classification.

SOURCES: U.S. Bureau of tile Census, 1980 Annual Survey of Manufactures, and Resource Dynamics Estimates. Presented in Resource Dynamics Corporation (1984).

new electrotechnologies" (ibid., p. 37). As Table 5-2 indicates, after motor drive, electrolytic processes and process heating are the two other most important classified industrial end uses for electricity. About electrolytic processing the report states (ibid.):

> 15 to 20 percent of all industrial electricity is used for electrolysis of aluminum and chlorine (Boerker, 1979; Schmidt, 1984). Aluminum electrolysis is more likely to decrease than increase as a fraction of industrial use, because efficiency improvements of 20 to 30 percent are technically possible from several technologies and are probably necessary (given sharply increasing prices for electricity in the Northwest, Texas, and Louisiana where plants have been located) to keep aluminum production in the United States competitive with aluminum production overseas.

About process heating the report goes on to say (ibid.):

> Electric process heating in industry accounts for only about 10 percent of current uses of electricity but has great potential to become much more important as new electric process heating techniques are developed that make better use of electricity's precision and ability to produce very high temperatures. In some important high temperature industries such as cement, iron and steel, and glassmaking, electricity makes up 20 to 35 percent of all energy use and could as much as double its share.

In summary, then, some important determinants of future industrial electricity use are the relative growth rates of the electricity-intensive and the non-electricity-intensive industries; the introduction of new, more efficient electric motors to replace existing, less efficient models; and the introduction of new industrial electrotechnologies. The prices of electricity and alternative fuels will also be important in influencing future electricity use in this sector. Such price trends will De important as well in influencing sectoral productivity growth trends, as discussed in Chapter 3, and in realizing the benefits that can be obtained from the newer, more efficient electricity-using technologies discussed in Chapter 4.

The Commercial Sector

As Chapter 2 showed, commercial electricity consumption has grown the fastest of that in any of the three main sectors of the economy, at least since 1960, reaching about 28 percent of all use by 1983. This owes partly to the growth in output and employment in the commercial part of our economy. Table 2-3 pointed out, for example, that between 1950 and 1983 the commercial sector increased from 62 to 69 percent of U.S. GPO. Table 2-4 showed that employment in the commercial sector grew from 55 to 71 percent of the U.S. labor force between those same years. About 55 percent of the commercial sector's energy use is for heating and air conditioning; about 35 percent is for lighting; the remainder is for applications such as water heating, cooking, refrigeration, and operating miscellaneous appliances.

Projecting the trends in commercial electricity use is easier in principle than in practice. In principle, commercial building stock and the electricity use per building in that stock are the pertinent measures to analyze and predict. Growth in commercial building stock is related to growth in commercial economic activity. Determining electricity use per building, however, is extremely difficult for two reasons. First, only poor data are available on the electricity-using characteristics of the existing commercial building stock. The Nonresidential Building Energy Consumption Survey (NBECS) (U.S. Energy Information Administration, 1983) is a good start at assembling this data base, but projecting additions to this stock is problematic. Second, it is hard to assess how various determinants of future electricity use in this stock—such as the prices of electricity and alternative fuels, heating and cooling equipment efficiencies, building envelope designs, and various retrofit measures—will affect the electricity use in both existing and new commercial building stock.

The Office of Technology Assessment reviewed the prospects for future electricity consumption patterns, reaching the following conclusions (U.S. Congress, 1984, p. 41):

> Electricity use per square foot in commercial buildings may continue to increase for several reasons. Only 24 percent of the existing commercial building square footage but almost half (48 percent) of new building square footage is electrically heated (U.S. Energy Information Administration, 1983) Air conditioning in commercial buildings is probably saturated. About 80 percent of all buildings have some air conditioning. . . . Greater use of office machines and automation might increase electricity use both to power the machines and to cool them in office buildings, stores, hospitals, and schools. Machines, however, are less likely in churches, hotels, and other categories of commercial buildings.

The potential for improving the efficiency of electricity use in buildings is significant. Several studies (U.S. Congress, Office of Technology Assessment, 1982; Solar Energy Research Institute, 1981; Meier et al., 1983; Hunn et al., 1985) conclude that electricity and fuel use in commercial buildings can be reduced by a significant fraction. One of these recent reports (U.S. Congress, Office of Technology Assessment, 1982), for example, found that electricity use for lighting and air conditioning in commercial buildings could be reduced by one-third to one-half and that the heating requirements also could also be reduced substantially by recycling heat generated by lighting, people, and office machines from the building core to the periphery. Unfortunately, it is not easy to predict either to what extent owners and managers of existing buildings will be motivated to take advantage of these technical opportunities or to what extent new buildings will approach their energy efficiency potentials.

Higher fuel and electricity prices increase the incentives to improve equipment and building efficiencies, as do a variety of public policy measures that have this end. Beyond this observation, the exact nature of the incentives and how successful they will be in motivating reduced use of electricity and other fuels is hard to assess. Conservation potentials and practices are discussed in a later section.

The Residential Sector

In 1983 residential electricity use stood at about 34 percent of total use. Chapter 2 reported that the trends in such use through 1983 have been of consistent increase in use per customer and of consistent increase in the number of customers served. Future residential electricity consumption depends on the total number of households and on the use per household. The number of households is a function of population and household size. The use per household is a function of the particular uses in the principal end-use categories, as in the historical patterns illustrated in Figures 2-8 and 2-9.

What are the prospects for residential electricity use in light of these measures? A quantitative answer to this question is, as before, beyond the scope of the committee's inquiry. Some important influences on future residential electricity use, however, are discussed below.

Household formation is a complex function of a number of demographic, sociological, and economic variables. Recent trends in household formation have been summarized as follows (U.S. Congress, Office of Technology Assessment, 1984, p. 39):

> Over the decade from 1970 to 1980, the U.S. population formed households at a rate much faster than population growth. In current census projections, this trend is expected to continue through the 1980s, resulting in a fairly rapid rate of household formation of 2.2 percent per year and a further drop in household size from about 3.2 people per household in 1970 to 2.8 people in 1980 to 2.5 people per household in 1990. On the other hand, were the U.S. taste for living in smaller and smaller households to become less important, the growth rate in household formation could fall to 1 percent per year or less.

Regarding use per customer (or per household), there are potentially opposing influences. Growth in the penetration of electric heating and cooling tends to increase electricity use, while increasing appliance efficiency and building thermal performance tend to decrease use.

Any trend toward increasing use would come primarily from growth in electric space-conditioning applications. For example, as Chapter 2 reported:

> electricity continues to make significant inroads in space heating and air conditioning. While about 17 percent of the total occupied housing stock *today* uses electricity as its primary heating source, 50 percent of new single-family housing units (and a greater percentage of multifamily housing units) incorporate electric heating systems, up from 28 percent in 1970. Of all occupied housing units, 57 percent now have air-conditioning systems of some type, but only 27 percent are equipped with central air-conditioning systems. However, some two-thirds of new single-family homes are built with central air-conditioning systems, which indicates that such electricity penetration will continue.

There may be some increase in other electricity uses also (U.S. Congress, Office of Technology Assessment, 1984, pp. 39-40):

> The use of electricity to heat water may expand beyond the 30 percent of households that now use it and could as much as double if there is a big decrease in the relative cost of electric and gas-heated hot water. The demand for other electric appliances is considered largely saturated and unlikely to expand substantially beyond the demand caused by increases in new households.

A force in the other direction, however, is exerted by possible improvements in appliance, lighting, and building efficiencies. Table 5-3 illustrates one estimate of the potential for improving appliance and lighting efficiencies. The cited report noted that "most observers agree that some improvement in appliance efficiency will occur" (ibid., p. 40), because "continued increases in electricity prices will increase the demand for...high efficiency products [and] in some regions market incentives will be augmented by local utility programs" (ibid.).

Note also that none of the items listed in Table 5-3 concern the building envelope, or shell. A variety of known measures could significantly improve the thermal performance of building envelopes (Solar Energy Research Institute, 1981; Hunn et al., 1985). These measures encompass window coatings, insulation and weather stripping, and a variety of window shadings.

Some local and state governments are sponsoring programs to increase the incentives to adopt some of the conservation measures above. Some utilities and regulatory agencies are also actively promoting these programs.

Beyond these points, future electricity and fuel prices will play an important role in consumer choices that achieve residential electricity conservation. We turn, then, to discussing the likely effects of price movements.

TABLE 5-3 Efficiencies of Typical and Best Household Appliances (1982 Models) and Potential Increases in Efficiency from Typical to Best

Household Appliance	Typical 1982 Model	Most Efficient 1982 Model	Potential Increase in Efficiency (Percent)
Heat pump (COP)[a]	1.7	2.6	+ 53
Electric hot water heater (COP)[a]	0.78	2.2	+ 182
Room air conditioner (EER)[b]	7.0	11.0	+ 57
Central air conditioner (SEER)[c]	7.6	14.0	+ 84
No-frost refrigerator-freezer (energy factor)[d]	5.6	8.7	+ 55
Chest freezer (energy factor)[d]	10.8	13.5	+ 25
Bulb producing 1,700 lumens (efficacy in lumens/W)[e]	17	40	+ 135

[a] COP is the coefficient of performance, thermal output (in kWh) divided by electrical input (in kWh).

[b] EER is the energy-efficient ratio obtained by dividing cooling power (in Btu/h) by electrical power input (in W).

[c] SEER is a seasonal energy-efficient ratio standarized in a U.S. Department of Energy test procedure.

[d] Energy factor is the corrected volume divided by daily electricity consumption, where corrected volume is the refrigerated space plus 1.63 times the freezer space for refrigerator-freezers and 1.73 times the freezer space for freezers.

[e] 1,700 lumens is the output of a 100-W incandescent bulb.

SOURCE: Derived from Howard S. Geller, Efficient Residential Appliances: Overview of Performance and Policy Issues, American Council for an Energy Efficient Economy, July 1983. Presented in U.S. Congress, Office of Technology Assessment (1984).

PRICES OF ELECTRICITY AND OTHER FUELS

General Price Considerations

Numerous effects have been traced to the relative shifts in energy prices of the 1970s and early 1980s. In particular, we have witnessed greater efficiencies in electricity use and the substitution of electricity for oil and gas, since these fuels have increased in price much faster than electricity. Several studies cited in Chapter 2 concluded that electricity and alternative fuel prices enter into electricity demand, but that their quantitative effects are not yet well established. Another effect of increasing fuel prices, as Chapter 3 reported, has been reduced productivity growth in the general economy.

The central question about price in the context of this report is different: what will future fuel and electricity prices mean for the future electricity use-GNP relationship? Stated differently, if electricity prices increase or decrease relative to other fuel prices or other prices in the economy, what will the effects be on electricity use?

For relatively constant fuel and electricity prices, there is likely to be little shift in the relationship. Continued disruption in the fuels markets and future fuel price increases like those experienced since 1973 would have a depressing effect on productivity growth and foster further efficiency of electricity use, sustaining (or forcing a return to) the energy awareness of the 1970s.

Electricity prices are, of course, a composite of costs of the fuels to generate the electricity and of a large number of capital and labor costs for generating, transmitting, and distributing the electricity. The ultimate consumer price, both in the past and in the future, is a reflection of such costs as administered through state regulation.

Regional Price Considerations

Electricity prices vary around the country, in part because electricity is produced in the United States by individual utilities with different resource bases, fuel mixes, and other variations. Prices vary also because they are set by individual state utility commission reviews, for investor-owned utilities, and by individual local communities, for municipal utilities.

Future electric service requirements will also affect future electricity prices. As discussed in Appendix B, electric service has two characteristics, instantaneous demand and cumulative use. Though fuel use is determined primarily by cumulative use, instantaneous demand determines whether utilities must build additional facilities to supply power their customers need. The cost of cumulative use is an operating cost, largely determined by fuel prices. The cost of meeting growth in instantaneous demand, on the other hand, requires capitalization of new generating equipment. In recent years the costs of new equipment have generally been greater than those of existing facilities. Thus, areas of the country that face increasing instantaneous demand may face greater price increases than those where electricity use does not require new capacity. As a result, electricity use, which is related to economic output—as affected by electricity prices and productivity gains, will in turn vary regionally.

Regional variation in electricity prices also occurs because of rate design. For example, where utilities have time-of-use rates (reflecting the cost differential in meeting variable customer demand as different parts of the utility's generating capacity are used), users whose demand falls mostly on peak, when demand is greatest, will face the largest utility bills. Their ability to shift demand off peak will reduce both their electricity costs and the need for the utility to build new facilities.

Other trends in rate-making practices will also affect future electricity prices. One of these trends is to make electricity prices more "forward looking," through using marginal-cost pricing and "forward" test years rather than historical test years. Another trend is to differentiate rates according to the reliability of service, allowing the consumer to choose from a variety of reliability levels and their corresponding rates.

Effects of Price on Electricity Use

It is hard to assess how these various influences will combine to affect future electricity use. The result depends on exactly what price changes come about and how. For example, a change in electricity prices caused by changing fuel prices has a different effect than the same change caused by a change in the real cost of installing new generating plants. The different effects will be related to the price elasticities of electricity demand with respect to electricity and alternative fuels, and to the influence of the price changes on productivity growth rate.

Consider first a case where an electricity price increase is brought about by a change in fuel prices only. Assume the elasticity of electricity demand with respect to alternative fuel prices is about one-third of the own-price elasticity of electricity and opposite in sign. Fuel prices represent about one-third to one-half the cost of producing electricity. Thus, doubling fuel prices would result in electricity prices rising by one-third to one-half. On the one hand the effect of the higher fuel prices would be to make electricity more attractive relative to alternative fuels, tending to increase electricity use; on the other hand the effect of the higher electricity prices would be to discourage electricity use. The price effects, at least for these elasticities, approximately offset one another.

Contrast this case with a hypothetical increase in the price of electricity brought about only by a change in the cost of generating plants, with no offsetting change in alternative fuel prices.

If we carry the effects of the fuel and electricity price changes through to productivity growth rate, as discussed in Chapter 3, then the situation becomes more complex. In the first case above, both the fuel and electricity price increases will tend to decrease the rate of productivity growth in many industries. This decreased productivity growth rate will show up directly in decreased GNP growth rate and therefore in decreased electricity consumption, at least according to the linear relationship between electricity use and GNP discussed in Chapter 2. In the second case, the increase in electricity prices will also tend to decrease the rate of productivity growth, but without the additional depressing effect on productivity growth rate traceable to increased alternative fuel prices. Thus, the reduction of productivity growth rate in the general economy will be somewhat larger if the electricity price change is a result of changing fuel prices than if the electricity price change is independent of fuel prices.

It is harder to determine the effects on electricity use of changes in electricity prices from allocating costs according to time-of-use. In some cases, the resulting cost allocation will depress growth in electricity end uses that occur predominately during peak periods, but at the same time it may stimulate consumption during off-peak periods. This shift of load has implications for the amount and type of generating equipment that might be used most economically to meet future instantaneous demand, thus influencing the future costs of electricity supply and, in turn, productivity growth. The data are not sufficient, however, to determine whether the net effect will be an increase or decrease in electricity use.

Other rate-making innovations would not seem to affect productivity growth directly much, though they may augment the effectiveness of, or substitute for, various conservation and load management programs, which are discussed in the next section.

PRACTICES AND POTENTIALS FOR EFFICIENCY IMPROVEMENTS: CONSERVATION AND LOAD MANAGEMENT

As pointed out earlier, the potential for improving the efficiency of electricity use is large, particularly for buildings and appliances. This section first discusses the nature and size of such potential; then it addresses the likelihood that a significant part of that potential will be realized; and, finally, it relates the efficiency and load management possibilities to productivity, as discussed in Chapters 3 and 4.

First, it is useful to make a distinction between conservation and load management. As the previous section pointed out, service requirements for electricity can be measured two ways. The demand for power at a particular point in time is called load, conveniently measured in kilowatts. The use of power over an interval of time results in a cumulative consumption of electrical energy, conveniently measured in kilowatt hours. In this section, actions designed to increase the efficiency of electrical energy use are called conservation; actions designed to improve the efficiency of supplying an instantaneous level of power, primarily during periods of peak demand, are called load management.

Utility Experience

Partial evidence about the potential for electric efficiency improvements can be obtained from the experience of a few major utilities. These utilities have evaluated direct involvement in conservation and load management with respect to direct investments in new supply facilities, and they have made their future investment plans accordingly. Pacific Gas and Electric Company (PG&E), the nation's largest privately owned utility, is planning a series of expenditures that will yield the equivalent of 3,201 megawatts (12.5 percent of total projected load) by the year 2004, and 10,784 gigawatt hours (8.0 percent of total sales) by the same year (Pacific Gas and Electric Company, 1984). These projected savings, to be achieved by direct PG&E expenditures, are over and above the conservation that is projected to occur during the same period as a result of "consumer response to rate increases and impacts of government mandated conservation standards." In other words, PG&E expects to be able to "build" the equivalent of three typically sized nuclear power plants, by the year 2004, in the form of efficiency improvements within its service territory.

Southern California Edison Company has been particularly innovative in load management. For example, a pilot program offers customers a financial incentive to pick their own level of uninterruptible demand and then give the utility the right to cut off demand in excess of that level during emergency periods. The amount of the incentive will vary depending on each customer's estimated peak demand and the level of uninterruptible demand selected by each customer.

Prospects for Realizing the Potential of Conservation and Load Management

There are three prominent reasons why conservation and load management are considered to have attractive, but unrealized, potential. First, inefficiencies exist in electricity use because of electricity pricing practices mentioned in the previous section. Second, many consumers simply do not have enough information on which to base rational consumption decisions. Third, there are conflicting interests between efficient building design and building cost that sometimes discourage economical investment in energy efficiency measures.

The classic example of such divergent interests occurs when the landlord's tenants pay their own utility bills: insulating the building might be highly cost-effective, but the landlord must weigh the cost of insulation against the expectation of recovering that cost through higher rents. Another example concerns new commercial office buildings: an initial investment in oversized thermal storage may be highly cost-effective from the point of view of the building operator, but those designing and constructing the building will not necessarily feel that economic stimulus. In commercial buildings in particular, this factor may loom large, since builders and owner-operators are rarely the same; nor are owner-operators and tenants usually the same. Such conflicts will be reduced only to the extent that information about potential efficiencies becomes commonly available to office building purchasers and that those purchasers insist on such efficiencies as criteria for purchase.

The point is important in the present context because the conservation and load management programs being promulgated at all levels of government and by many electric utilities are designed to induce more efficient energy use to overcome exactly such impediments. Since it is generally accepted that industrial users already have incentives to use electricity efficiently in that industrial rates are closer to marginal costs than are residential and commercial rates, most of these programs are aimed at use in the last two sectors. However, most utilities will implement conservation and load management programs only if such programs are cost-effective for the entire set of utility rate payers and not simply a subset. This approach is somewhat different from the one that utility commissions embraced just a few years ago, namely, the approach that the entire class of conservation programs was worthwhile. The difficulty in measuring cost-effective conservation, particularly in the residential sector, is quite large. Further study would be appropriate.

All the cost-effective measures that can increase the efficiency of electricity use also offer prospective increases in various measures of productivity, as we illustrate with a few examples below.

Economic Effects

Consider the effects the more efficient appliances listed in Table5-3 would have if they were adopted in the residential sector. First, using these appliances would reduce the use of electricity, at least for corresponding end uses. Also, the consumers who chose these more efficient appliances would have paid more to acquire them, but they would also pay less on a monthly basis for electricity to enjoy the services the appliances provide. Any net savings over the life of the appliance would consist of income available for other consumption. However, none of these effects will show up in the sectoral productivity measures discussed in Chapter 3. Rather, the macroeconomic effect will be evidenced in a change in the composition of consumption and a change in the composition of sectoral output. Thus, although the new technologies offer more efficient service to the consumer than the old technologies with consequent increase in disposable income, they offer no direct benefits to macroeconomic productivity. The same principles would apply to improving building thermal characteristics in the residential sector.

Similar improvements in the commercial sector, however, would evidence themselves in measures of sectoral productivity growth. The commercial sector is an intermediate sector of production, employing capital, labor, materials, electricity, and nonelectrical energy to produce its output. To the extent that cost-effective building envelope, lighting, and appliance efficiency improvements can be made, the result will be evidenced in the sectoral productivity measures discussed in Chapter 3.

In like manner, the adoption by industry of one of the new electrotechnologies discussed in Chapter 4, as long as its use is more cost-effective than the technology it replaces, will show up as a productivity improvement, using the analysis of Chapter 3.

By the same reasoning, many improvements promulgated by the several levels of government and by utilities for increased efficiency of residential electricity use do not manifest the direct sectoral and macroeconomic benefits that similar improvements might afford in the industrial and commercial sectors.

In another way, however, all means of consuming electricity more efficiently, particularly those that reduce peak demands, are indirectly beneficial. This result comes about through effects on the costs of supply. The cost of supplying electricity during periods of peak demand exceeds that during baseload periods. In the long run, if peak loads can be reduced relative to total electricity sales, this means that less generating capacity can be used to produce the same number of kilowatt hours, reducing the average cost of generation. Any measure that offers a real reduction in the costs of supply was shown in Chapter 3 to induce productivity improvements.

In still another sense, any efficiency improvement, whether in supply or in consumption of electricity, offers economic benefit. Electric utilities provide a set of services to residential, commercial, and industrial customers, so that any decrease in the cost of a service, regardless of the source of the decrease, makes the supply of that service more efficient. It is improving productivity in this sense that leads many proponents of conservation and load management to advocate so strongly their conservation programs. Several studies have shown that there are many potential means for reducing electricity consumption that cost less than current supply; consequently, the thrust of the conservationist's argument is that to forgo these potentials is to lose economic efficiency and productivity.

One means of accomplishing the goal of reduced consumption is to encourage utilities to fund efficiency measures. As discussed above, many electric utilities in the United States have embarked on substantial programs toward electric efficiency to expand their effective service. Much of the potential for savings could be realized, given the willingness of residential, commercial, and industrial users to participate. Moreover, if investment in efficiency measures became conventional utility behavior nationwide, it could have a major educational effect on other potential investors.

Whether utilities in general will take on such economic activity is, of course, uncertain. The outcome will depend in part on both federal and state government policies, including those of state regulatory commissions, which often have the power to supervise future investments by individual regulated utilities. The outcome will also depend, in part, on institutional inertia, and on the extent of efforts to overcome it, within the utility industry itself. These efforts will depend in part on government leadership at both federal and state levels.

Some suggest that the prospects for realizing such potentials are uncertain or that they are exaggerated. Often, those holding these views suggest a different strategy for meeting future electricity needs, namely, by ensuring a plentiful and economical supply of electricity through constructing additional conventional power plants.

The rational response to this apparent conflict lies in comparing the available alternatives to determine the most economically sound and reliable mix. Because the potentials and costs, both for conservation and load management and for conventional power plant investments, may vary substantially from region to region and utility to utility, it is appropriate to conduct such analyses at the utility level, case by case.

THE OUTLOOK

To return to the questions raised at the beginning of this chapter, the principal forces that have shaped the relationship between electricity use and GNP in the past will probably continue to operate in the future. A linear relationship between the two quantities has persisted for many years, despite relatively large shifts in the composition of national output and large shifts in electricity and alternative fuel prices in the past decade. However, the forces of change operating on this relationship may be expected to take a long time to become evident, and perhaps not enough time for that has passed since the energy price shocks. The information presented in this chapter is not enough to make a judgment about the continuation of the former relationship.

There are a number of forces capable of altering the linear relationship in the future. A few examples are electrification brought about by technical change; conservation in response to price changes and heightened user awareness; regulatory actions, such as pricing policies; and other public policies affecting the availability and use of energy.

Electrification opportunities are illustrated by the new industrial electrotechnologies mentioned in Chapter 4, as well as a number of more efficient residential and commercial appliance and equipment alternatives reviewed in this chapter. However, in all three economic sectors electrification has long been proceeding and is thus already embodied in the trends portrayed in Chapter 2. In considering the future, no dramatic nor trend-changing options for electrification were identified, though many options that will continue incremental increases in electricity use were noted.

A variety of known conservation and load management opportunities have the potential for making electricity use more efficient. Some state regulatory authorities and utilities have been particularly effective at promoting the realization of such potential, for example, California regulators and utilities. However, in other states and in California as well, there is significant further potential for reducing electricity use, even though there are also significant institutional barriers to realizing this potential. Some conservation programs have been in effect for years, and as a consequence their effects are also already embodied in the data of Chapter 2. Future opportunities can be characterized as a continuation of the historical trends.

In the future, the state of the economy will probably continue to be the most important determinant of electricity use, as it has been in the past. Recall, in this connection, the strong conclusion of Chapter 3 that both the level and growth rate of the economy are smaller than if the energy price increases of the 1970s had not occurred. Nevertheless, we expect that other determinants of electricity use will continue to modulate the precise relationship.

In addition, we have established that many of the forces that will influence future electricity use will also affect growth in our economy through their influence on productivity. Actions that change real electricity prices, for example, affect productivity growth as well as the immediate and future use of electricity. Conservation actions that result in increased economic efficiency of electricity use offer productivity gains—if not directly, then indirectly. Selected electrotechnologies, whenever their use reduces the cost of output, also offer productivity benefits.

The interrelations pointed out here have not always been well understood, and much additional work should be done to quantify them. Moreover, the dual interaction between electricity and the economy, namely, the correlation of consumption with GNP and the effect of electricity-using technical change and electricity prices on the productivity growth rate, should be considered in developing federal and state energy and economic policies.

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Appendix A

Statement of Work

The subcontract between Los Alamos National Laboratory and the National Academy of Sciences provides that the Academy will form a committee of experts to assess the role of electricity in domestic economic growth. The stated objectives of the study are as follows:

1. Review relevant research on the interrelationship between electricity and economic growth in the United States. Indicate the degree to which electricity was historically important to U.S. economic growth and document the results.
2. Analyze changes taking place in the structure of the economy that could influence future trends of electricity demand growth, and identify possible relationships between economic growth and electricity requirements that may develop in the future.
3. Review the electricity consumption patterns that have experienced significant changes over the past decade, and indicate potential new electricity patterns.
4. Present the results of the study in a written report. The report will (a) review the importance and interrelationships between electricity and economic growth, (b) show how trends in electricity demand growth may be impacted by changes in the economy and what the particular relationships are that affect these trends, and (c) form a foundation for subsequent examination of electrification and productivity in particular industries and for examination of alternative demand and supply scenarios for electricity.

The sponsor also asked the committee to consider several auxiliary questions, intended to give additional structure and specificity to the general task. The questions, listed below, relate principally to two issues: electricity demand and productivity stemming from electricity use.

1. What is the relationship between electricity use and GNP? Is our measure of electricity use appropriate?

2. Has the basic demand function for electricity remained stable in recent history? What is the form of alternative demand functions and how do they interrelate?
3. What are likely to be the major determinants of electricity use over the next two or three decades? Do present methods of forecasting use adequately take these determinants into account? As measures of use, must peak load trends (in kilowatts) be treated differently than consumption trends (in kilowatt hours)?
4. Will structural changes in the economy, apart from utility efforts, affect future demand for electricity? If so, how? How is "structural change" defined for the purposes of this question?
5. How have the conditions of historical electricity supply influenced economic growth?
6. What are the implications of the conditions of future electricity supply for economic growth?
7. Does electricity supply affect our economic well-being beyond its measurable affect on GNP? If so, how?

Appendix B

Measures of Economic Growth and of Electricity Demand

One focus of this work is a better understanding of the relationships between economic growth and electricity demand.

Economic growth is conventionally measured in terms of gross national product (GNP), a measure of the output of the so-called productive economy, as distinguished from the residential sector, the output of which is not included in GNP. Yet a large part of electricity use occurs in households. Should electricity use then be considered here only for the productive economy to ensure the comparability of figures? This treatment is usually not adopted because the income generated by the productive economy is used for household expenditures.

In GNP each unit of electricity is valued at its price, for example, at 7 cents per kilowatt hour. Yet electricity certainly gives rise to costs external to its price, such as air pollution. It might be argued that these costs ought to be subtracted somehow from GNP. On the other hand, some tasks, such as instant communication between continents, could not be accomplished at any price without using electricity. Thus, electricity's special characteristics give rise to various positive and negative effects external to its price, not captured by the GNP indicator.

Similarly, conventional measures of electric service do not capture everything of importance for our purposes. Electric service is measured in terms of installed capacity to deliver power or of energy consumption. Electricity's full usefulness, however, lies in effective end-use service to customers—warmer homes, cooler office buildings, and many other applications—from electrically powered equipment. As discussed elsewhere in the report, a few of the nation's larger utilities are making major expenditures to increase the effective delivery of electric services to their customers without increasing either installed capacity or energy consumption as usually measured. The expenditures are for conservation and load management technologies, rather than for new power plants. Because these expenditures are being made by public utility companies expressly to expand the effective use of electricity, the conventional measures of electric service that a utility renders do not tell us all we need to know about the service's value. In other words, conventional measures of electricity may understate the actual amount of effective service provided.

We considered these measurement issues early and decided to rely on conventional measures of both electricity and economic growth because of the difficulty of doing otherwise and the need to conform with prior work. We simply recognize that the conventional measurements can sometimes be incomplete in significant ways.

We must also distinguish two uses of the word "demand" to avoid confusion. In the economic sense demand is the quantity of a commodity or service wanted at a specific price and time. Thus electricity demand, as related to economic activity, is usually measured in units of electrical energy, conveniently kilowatt hours. This concept is not the one most natural to utilities. Utilities think of electricity demand as the instantaneous load on the utility system, measured in units of electrical power that must be supplied at that time, usually kilowatts. Utilities think of electricity consumption over time as energy, measured in kilowatt hours.

We make this distinction because the vast majority of analyses that relate electricity consumption and economic growth focus on kilowatt hours. These studies do not consider the availability and cost issues of having sufficient capacity to meet demand in the sense that utilities define it. To understand the relationship between electricity consumption and economic growth we have to keep in mind that each kilowatt hour consumed can have a different availability and cost to the utility (and possibly a different price to the consumer) reflecting the time and way it is produced. Availability and price will also vary with other features of the utility providing the electricity—its plant mix, fuel mix, reserve margin, and so on.

Ideally we would look at the relationships both between growth in instantaneous electricity demand (kilowatts) and that in GNP and between electricity consumption (kilowatts hours) and GNP. Although the former has received relatively little attention from economists, it remains a central issue for the companies providing the electricity and for utility regulators.

The distinction between kilowatts and kilowatt hours is important because electricity cannot be economically stored. Thus, providers of electricity, such as electric utilities, must have enough generating capacity available to meet the aggregate instantaneous demand on their systems that may result from the combined demands of each of their customers.

The efficiency with which a utility's generating capacity is used is a function of its load curve, that is, the hourly distribution of aggregate demand. If there is a substantial difference between average power supplied over a long term and peak power capability, then the utility's plant may not be used very efficiently. Thus, it is important to consider both measures if one is interested in adequacy and efficient allocation of resources.

The time pattern of growth in electricity demand (in kilowatts) is not the same as that of the growth in electricity use (in kilowatt hours). The Edison Electric Institute's (EEI) 1983 Electric Power Annual Report shows that from 1979 to 1983 the average growth per year for summer peak demand in the United States was 2.9 percent per year and for winter peak demand 2.7 percent per year, while the average growth in electricity use per year during the same period was only 1.0 percent per year. These data show that, since 1979, peak demand has on average grown faster than electricity use. However, including estimated 1984 data would make a large difference, because they tentatively show an increase in kilowatt hour use of 4.5 percent, with only 0.7 percent increase in noncoincident summer peak demand (winter data are not yet available). Without the 1984 data one might be inclined to infer that peak demand has begun to grow a good deal faster than electricity use, suggesting a deterioration in utility load curves and thus less efficient use of available generating capacity. Table B-1 does show a fairly steady decline in annual load factor since 1963. However, the 1984 data show an increase in load factor that is consistent with the greater increase in kilowatt hour use. It is too early to tell whether the divergence of kilowatt and kilowatt hour growth is a trend or not.

Electricity demand, like economic growth, shows significant regional variation. Table B-2 is a summary of data from EEI's 1983 Electric Power Annual Report. The map in Figure B-1 shows the geographical boundaries of the electric reliability council regions, which are subsets of the National Electric Reliability Council (NERC), used in EEI's planning and analysis. The summer peak demand compound growth rate for 1979 through 1983 varied from 0.7 percent per year in the MAIN region (Illinois, most of Wisconsin, and part of Missouri) to 5.9 percent per year in the ERCOT region (most of Texas). The next greatest area of growth was the southeastern United States. Winter peak demand also grew most rapidly in Texas and in the Southeast. Note that summer and winter peak load growth differ in most regions. (The line in this table designated "Entire United States" should be viewed with great caution. EEI notes that "U.S. totals are meaningless and should not be used for policy purposes.")

Growth of electricity use also varied greatly by region, ranging from an increase of 3.6 percent per year in Texas to a decline of 1.0 percent per year in the ECAR region. There is not a strong relationship between growth of peak demand and that of energy use except that in each region peak demand growth exceeded the increase in energy use over this period. However, recall that in 1984 energy use grew much faster than peak demand. Unfortunately regional data are not available for 1984. The aggregate 1984 figure suggests that we should be cautious about inferring a relationship between peak demand growth and energy use demand growth between 1979 and 1983, since including 1984 data would significantly change any relationship inferred.

TABLE B-1 Capability, Peak Load, and Kilowatt Hour Requirements, for the Total Electric Utility Industry Excluding Alaska and Hawaii, 1963 to 1984

Year	Capability at Time of Summer Peak Load (MW)[a]	Noncoincident Summer Peak Load (MW)	Capability at Time of Winter Peak Load (MW)[b]	Noncoincident Winter Peak Load (MW)[b]	Capacity Margin Based on Noncoincident Peak Load (Percent)[bc]	Annual Kilowatt Hour Requirements (in Millions)	Annual Load Factor Based on Peak Load (Percent)
1984[d]	603,000	450,567	N/A	N/A	25.3	2,447,148	61.8
1983[e]	596,449	447,526	611,637	410,779	25.0	2,341,633	59.7
1982[f]	586,142	414,909	596,930	373,318	29.2	2,258,744	62.1
1981	572,219[f]	428,295	581,084	391,106	25.2[f]	2,311,006	61.6
1980	558,237[f]	427,058	572,195	384,567	23.5[f]	2,292,718	61.1
1979	544,506[f]	398,424	554,525	368,876	26.8[f]	2,246,927	64.4
1978	545,700	408,050	561,550	383,100	25.2[f]	2,218,700	62.1
1977	516,000	396,350	537,600	360,200	23.2[f]	2,132,300	61.4
1976	498,750	370,900	511,000	349,850	25.6[f]	2,039,500	62.6
1975	479,300	356,800	492,450	331,100	25.6[f]	1,919,500	61.4
1974	444,400	349,250	467,400	302,500	21.4[f]	1,871,700	61.2
1973	415,500	343,900	433,150	295,100	17.2[f]	1,868,800	62.0
1972	381,700	319,150	394,050	290,950	16.4[f]	1,752,200	62.5
1971	353,250	292,100	366,700	261,650	17.3[f]	1,617,100	63.2
1970	326,900	274,650	339,050	248,550	16.0[f]	1,536,400	63.9
1969	300,300	257,650	311,450	236,600	14.2[f]	1,446,000	64.1
1968	278,950	238,000	288,750	226,700	14.7[f]	1,327,200	63.5
1967	257,950	213,450	267,750	205,850	17.3[f]	1,221,500	65.3
1966	240,700	203,350	247,650	193,700	15.5[f]	1,152,900	64.7
1965	228,900	186,300	235,700	180,400	18.6[f]	1,060,100	65.0
1964	216,500	175,000	222,400	171,100	19.2[f]	986,800	64.2
1.963	205,300	159,450	210,000	161,300	23.2(w)[f]	921,800	65.2

[a] Capability represents the maximum kilowatt output with all power sources available and with hydraulic equipment under actual water conditions. Capability provides the necessary allowance for maintenance, emergency outages, and system operating requirements. This rating is more indicative of the actual generating ability of existing power stations than the familiar name-plate rating.

[b] Beginning in 1973, capability and peak load data shown for winter represent those turn-of-year data for the winter season that follows the summer peak load data for that calendar year. Previously, data in this series were always calculated for tile month of December.

[c] Calculated from the maximum noncoincident peak load, summer or winter, and the capability at the time of this peak load. Percent capacity margin is the difference between capability and peak load divided by capability multiplied by 100. A "w" indicates that the noncoincident peak load, summer or winter, occurred during winter of that year.

[d] Estimated.

[e] Preliminary.

[f] Revised data.

SOURCE: Adapted from Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry, 1983.

TABLE B-2 Compound Growth Rate in Peak Loads and Energy Requirements, by Region, 1979 to 1983 (Percent per Year)

Region[a]	Summer Peak Load Growth	Winter Peak Load Growth	Annual Growth in Energy Requirements
NPCC	2.1	0.9	1.1
MAAC	2.3	2.0	1.2
ECAR	1.7	1.7	-1.0
SERC	4.0	2.6	1.7
MAIN	0.7	0.6	-0.8
SPP	5.1	6.1	3.2
ERCOT	5.9	8.5	3.6
MAPP	3.5	2.2	1.5
WSCC	2.0	2.5	0.6
Entire U.S.	2.9	2.7	1.0

[a] See Figure B-1 for explanation of region acronyms.

SOURCE: Edison Electric Institute, 1983 Electric Power Annual Report, pp. 7-10 (data from National Electricity Reliability Council).

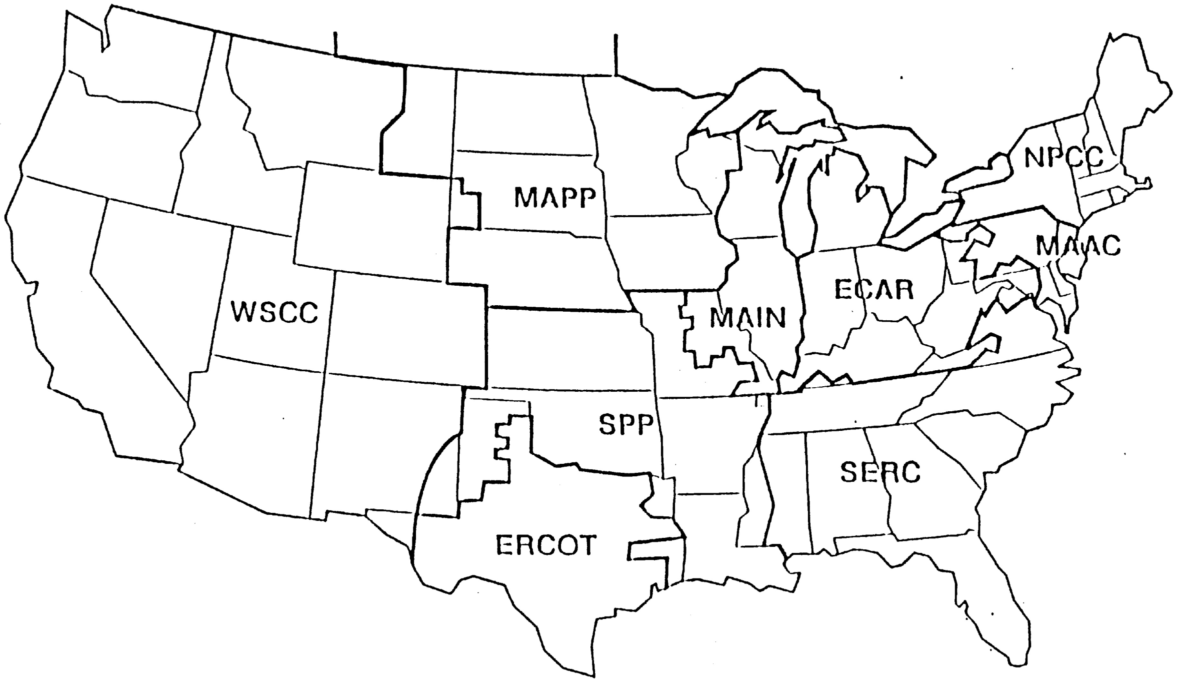

Figure B-1
U.S. Regions of the North American Electric Reliability Council (ECAR, East Central Area Reliability Coordination Agreement; ERCOT, Electric Reliability Council of Texas; MAAC, Mid-Atlantic Area Council; MAIN, Mid-America Interpool Network; MAPP, Mid-Continent Area Power Pool; NPCC, Northeast Power Coordinating Council; SERC, Southeastern Electric Reliability Council; SPP, Southwest Power Pool; WSCC, Western Systems Coordinating Council).

As Table B-3 shows, the NERC regional 'councils predict that growth in kilowatt hour use will equal or exceed peak demand growth in most regions over the next decade. They also project that on average annual load factors will remain constant over the next decade, at about the 1984 level. (The predicted value is 61.7 percent for 1984 to 1993 from 1983 Electric Power Annual Report, p. 24; the predicted value is 61.8 percent for 1984 from the EEI Statistical Yearbook.) Thus, the decline in load factor between 1979 and 1983 is expected by the councils to be arrested but not significantly improved over the next decade. Although this is clearly the intent of the councils, recent history suggests that it may not be easy to improve the growth of kilowatt hours over kilowatts. However, the interest expressed by various utilities in load management techniques suggests that there will be considerable emphasis placed on this goal over the next decade.

What does all this suggest about the relationship between GNP and electricity demand? It shows that the different concepts of demand have different growth predictions and that major variations in growth by region have been the norm and should be expected in the future. It also argues for disaggregating GNP growth by region to characterize past trends in the relationship between electricity use and GNP growth and to predict future trends better. Electricity can be transported, but there are limits to the distances over which it is efficient to do so. Centers of economic development may shift over time, but substantial lead times and capital expenditures are required. EEI predicts summer capacity reserve margins in 1993 that are higher in the areas where less demand growth is likely to occur and that range from 15.5 percent in the ERCOT region to 26.3 percent in the WSCC region. It predicts winter margins in 1993 from 24.4 percent in the SERC region to 37 percent in the SPP region. Interregional power sales can help equilibrate much of the mismatch of supply and demand and will help maximize efficient general use of resources.

TABLE B-3 Projections of Growth in Annual Load and Energy Requirements, by Region, 1984 to 1993 (Percent per Year)

Region[a]	Summer Peak Load Growth	Winter Peak Load Growth	Annual Growth in Energy Requirements
NPCC	1.7	1.8	1.9
MAAC	1.3	2.1	1.8
ECAR	2. 4	2. 5	2. 4
SERC	2.9	2.4	3. 0
MAIN	1.8	2.3	2.3
SPP	2.7	3.1	3. 0
ERCOT	4.0	4.1	4.0
MAPP	2. 4	2. 7	2. 9
WSCC	2.6	2.2	2.5
Entire U.S.	2.5	2.5	2.7

[a] See Figure B-1 for explanation of region acronyms.

SOURCE: Edison Electric Institute, 1983 Electric Power Annual Report, pp. 20-24 (data from National Electricity Reliability Council).

Appendix C

Econometric Model of Production and Technical Change

The following material gives a detailed description of the econometric model of production and technical change that underlies Chapter 3. * The quantity VT, here called "rate of technical change," is called "productivity growth rate" in the text of Chapter 3. The quantities β_{KT}, β_{LT}, β_{ET}, β_{NT}, and β_{MT}, here called "biases of technical change with respect to price," are called "biases of productivity growth with respect to price" in the text of Chapter 3.

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* Excerpted by permission from D. W. Jorgenson, The Role of Energy in Productivity Growth. EPRI EA-3482, Research Project 1152-6, Final Report. Palo Alto, California: Electric Power Research Institute. May, 1984.

TECHNICAL APPENDIX

The development of our econometric model of production and technical change proceeds through two stages. We first specify a functional form for the sectoral price functions, say $\{p^i\}$, taking into account restrictions on the parameters implied by the theory of production. Secondly, we formulate an error structure for the econometric model and discuss procedures for estimation of the unknown parameters.

Our first step in formulating an econometric model of production and technical change is to consider specific forms for the sectoral price function $\{p^i\}$:

$$
\begin{aligned}
q_i = [\alpha_0^i &+ \alpha_K^i \ln p_K^i + \alpha_L^i \ln p_L^i + \alpha_E^i \ln p_E^i + \alpha_N^i \ln p_N^i + \alpha_M^i \ln p_M^i + \alpha_T^i \cdot T \\
&+ \tfrac{1}{2} \beta_{KK}^i (\ln p_K^i)^2 + \beta_{KL}^i \ln p_K^i \ln p_L^i + \beta_{KE}^i \ln p_K^i \ln p_E^i \\
&+ \beta_{KN}^i \ln p_K^i \ln p_N^i + \beta_{KM}^i \ln p_K^i \ln p_M^i + \beta_{KT}^i \ln p_K^i \cdot T + \tfrac{1}{2} \beta_{LL}^i (\ln p_L^i)^2 \\
&+ \beta_{LE}^i \ln p_L^i \ln p_E^i + \beta_{LN}^i \ln p_L^i \ln p_N^i + \beta_{LM}^i \ln p_L^i \ln p_M^i + \beta_{LT}^i \ln p_L^i \cdot T \\
&+ \tfrac{1}{2} \beta_{EE}^i (\ln p_E^i)^2 + \beta_{EN}^i \ln p_E^i \ln p_N^i + \beta_{EM}^i \ln p_E^i \ln p_M^i + \beta_{ET}^i \ln p_E^i \cdot T \\
&+ \tfrac{1}{2} \beta_{NN}^i (\ln p_N^i)^2 + \beta_{NM}^i \ln p_N^i \ln p_M^i + \beta_{NT}^i \ln p_N^i \cdot T \\
&+ \tfrac{1}{2} \beta_{MM}^i (\ln p_M^i)^2 + \beta_{MT}^i \ln p_M^i \cdot T + \tfrac{1}{2} \beta_{TT}^i \cdot T^2] \text{ , } (i = 1, 2 \ldots n). \qquad (1)
\end{aligned}
$$

For these price functions, the prices of outputs are transcendental or, more specifically, exponential functions of the logarithms of the prices of capital (K), labor (L), electricity (E), nonelectrical energy (N) and materials (M) inputs. We refer to these forms as transcendental logarithmic price functions or, more simply, translog price functions, indicating the role of the variables that enter into the price functions.

1. Homogeneity and symmetry. The price functions $\{p^i\}$ are homogeneous of degree one in the input prices. The translog price function for an industrial sector is characterized by homogeneity of degree one if and only if the parameters for that sector satisfy the conditions:

$$
\begin{aligned}
\alpha_K^i + \alpha_L^i + \alpha_E^i + \alpha_N^i + \alpha_M^i &= 1 \text{ ,} \\
\beta_{KK}^i + \beta_{KL}^i + \beta_{KE}^i + \beta_{KN}^i + \beta_{KM}^i &= 0 \text{ ,} \\
\beta_{LK}^i + \beta_{LL}^i + \beta_{LE}^i + \beta_{LN}^i + \beta_{LM}^i &= 0 \text{ ,} \\
\beta_{EK}^i + \beta_{EL}^i + \beta_{EE}^i + \beta_{EN}^i + \beta_{EM}^i &= 0 \text{ ,} \\
\beta_{NK}^i + \beta_{NL}^i + \beta_{NE}^i + \beta_{NN}^i + \beta_{NM}^i &= 0 \text{ ,} \\
\beta_{MK}^i + \beta_{ML}^i + \beta_{ME}^i + \beta_{MN}^i + \beta_{MM}^i &= 0 \text{ ,} \\
\beta_{KT}^i + \beta_{LT}^i + \beta_{ET}^i + \beta_{NT}^i + \beta_{MT}^i &= 0 \text{ ,} \qquad (i = 1, 2 \ldots n). \qquad (2)
\end{aligned}
$$

For each sector the value shares of capital, labor, electricity, nonelectrical energy, and materials inputs, say $\{v_K^i\}$, $\{v_L^i\}$, $\{v_E^i\}$, $\{v_N^i\}$, and $\{v_M^i\}$ can be expressed in terms of logarithmic derivatives of the sectoral price functions with respect to the logarithms of price of the corresponding input:

$$\begin{aligned}
v_K^i &= \alpha_K^i + \beta_{KK}^i \ln p_K^i + \beta_{KL}^i \ln p_L^i + \beta_{KE}^i \ln p_E^i + \beta_{KN}^i \ln p_N^i + \beta_{KM}^i \ln p_M^i + \beta_{KT}^i \cdot T \,, \\
v_L^i &= \alpha_L^i + \beta_{KL}^i \ln p_K^i + \beta_{LL}^i \ln p_L^i + \beta_{LE}^i \ln p_E^i + \beta_{LN}^i \ln p_N^i + \beta_{LM}^i \ln p_M^i + \beta_{LT}^i \cdot T \,, \\
v_E^i &= \alpha_E^i + \beta_{KE}^i \ln p_K^i + \beta_{LE}^i \ln p_L^i + \beta_{EE}^i \ln p_E^i + \beta_{EN}^i \ln p_N^i + \beta_{EM}^i \ln p_M^i + \beta_{ET}^i \cdot T \,, \\
v_N^i &= \alpha_N^i + \beta_{KN}^i \ln p_K^i + \beta_{LN}^i \ln p_L^i + \beta_{EN}^i \ln p_E^i + \beta_{NN}^i \ln p_N^i + \beta_{NM}^i \ln p_M^i + \beta_{NT}^i \cdot T \,, \\
v_M^i &= \alpha_M^i + \beta_{KM}^i \ln p_K^i + \beta_{LM}^i \ln p_L^i + \beta_{EM}^i \ln p_E^i + \beta_{NM}^i \ln p_N^i + \beta_{MM}^i \ln p_M^i + \beta_{MT}^i \cdot T \,, \\
& \qquad (i = 1, 2 \ldots n). \qquad (3)
\end{aligned}$$

Finally, for each sector the rate of technical change, say $\{v_T^i\}$, can be expressed as the negative of the rate of growth of the price of sectoral output with respect to time, holding the prices of capital, labor, electricity, nonelectrical energy, and materials inputs constant. The negative of the rate of technical change takes the following form:

$$\begin{aligned}
-v_t^i &= \alpha_T^i + \beta_{KT}^i \ln p_K^i + \beta_{LT}^i \ln p_L^i + \beta_{ET}^i \ln p_E^i + \beta_{NT}^i \ln p_N^i + \beta_{MT}^i \ln p_M^i + \beta_{TT}^i \cdot T \,, \\
& \qquad (i = 1, 2 \ldots n) \,. \qquad (4)
\end{aligned}$$

Given the sectoral price functions $\{p^i\}$, we can define the share elasticities with respect to price[19] as the derivatives of the value shares with respect to the logarithms of the prices of capital, labor, electricity, nonelectrical energy, and materials inputs. For the translog price functions the share elasticities with respect to price are constant. We can also characterize these forms of constant share elasticity or CSE price functions indicating the interpretation of the fixed parameters that enter the price functions. The share elasticities with respect to price are symmetric, so that the parameters satisfy the conditions:

$$\begin{aligned}
\beta_{KL}^i &= \beta_{LK}^i \,, & \beta_{LN}^i &= \beta_{NL}^i \,, \\
\beta_{KE}^i &= \beta_{EK}^i \,, & \beta_{LM}^i &= \beta_{ML}^i \,, \\
\beta_{KN}^i &= \beta_{NK}^i \,, & \beta_{EN}^i &= \beta_{NE}^i \,, \\
\beta_{KM}^i &= \beta_{MK}^i \,, & \beta_{EM}^i &= \beta_{ME}^i \,, \\
\beta_{LE}^i &= \beta_{EL}^i \,, & \beta_{NM}^i &= \beta_{MN}^i \,, \\
& & & \qquad (i = 1, 2 \ldots n) \,. \qquad (5)
\end{aligned}$$

---

[19] The share elasticity with respect to price was introduced by Christensen, Jorgenson, and Lau (1971, 1973) as a fixed parameter of the translog production function. An analogous concept was employed by Samuelson (1973). The terminology is due to Jorgenson and Lau (1983).

Similarly, given the sectoral price functions $\{p^i\}$, we can define the biases of technical change with respect to price as derivatives of the value shares with respect to time.[20]

Alternatively, we can define the biases of technical change with respect to price in terms of the derivatives of the rate of technical change with respect to the logarithms of the price of capital, labor, electricity, nonelectrical energy, and materials inputs. Those two definitions of biases of technical change are equivalent. For the translog price functions the biases of technical change with respect to price are constant; these parameters are symmetric and satisfy the conditions:

$$\begin{aligned} \beta^i_{KT} &= \beta^i_{TK}, \\ \beta^i_{LT} &= \beta^i_{TL}, \\ \beta^i_{ET} &= \beta^i_{TE}, \\ \beta^i_{NT} &= \beta^i_{TN}, \\ \beta^i_{MT} &= \beta^i_{TM}, \end{aligned} \qquad (i = 1, 2 \ldots n). \qquad (6)$$

Finally, we can define the rate of change off the negative of the rate of technical change β^i_{TT} (i = 1, 2 ... n) as the derivative of the negative of the rate of technical change with respect to time. For the translog price functions these rates of change are constant.

2. Concavity. Our next step in considering specific forms of the sectoral price functions $\{p^i\}$ is to derive restrictions on the parameters implied By the fact that the price functions are increasing in all five input prices and the concave in the five input prices. First, since the price functions are increasing in each of the five input prices, the value shares are nonnegative:

$$\begin{aligned} v^i_K &\geq 0, \\ v^i_L &\geq 0, \\ v^i_E &\geq 0, \\ v^i_N &\geq 0, \\ v^i_M &\geq 0, \end{aligned} \qquad (i = 1, 2 \ldots n). \qquad (7)$$

Under homogeneity these value shares sum to unity:

$$v^i_K + v^i_L + v^i_E + v^i_N + v^i_M = 1, \qquad (i = 1, 2 \ldots n). \qquad (8)$$

---

[20] The bias of productivity growth was introduced by Hicks (1932). An alternative definition of the bias of productivity growth was introduced by Binswanger (1974a, 1974b). The definition of bias of productivity growth to be employed in our econometric model is due to Jorgenson and Lau (1983).

Concavity of the sectoral price functions $\{p^i\}$ implies that the matrices of second-order partial derivatives $\{H^i\}$ are negative semi-definite, [21] so that the matrices $\{U^i + v^i v^{i\prime} - V^i]$ are negative semi-definite, where:[22]

$$\frac{1}{p^i} \cdot Q^i \cdot H^i \cdot Q^i = U^i + v^i v^{i\prime} - V^i , \qquad (i = 1, 2 \ldots n).$$

where:

$$Q^i = \begin{bmatrix} p_K^i & 0 & 0 & 0 & 0 \\ 0 & p_L^i & 0 & 0 & 0 \\ 0 & 0 & p_E^i & 0 & 0 \\ 0 & 0 & 0 & p_N^i & 0 \\ 0 & 0 & 0 & 0 & p_M^i \end{bmatrix} , \quad V^i = \begin{bmatrix} v_K^i & 0 & 0 & 0 & 0 \\ 0 & v_L^i & 0 & 0 & 0 \\ 0 & 0 & v_E^i & 0 & 0 \\ 0 & 0 & 0 & v_N^i & 0 \\ 0 & 0 & 0 & 0 & v_M^i \end{bmatrix} , \quad v^i = \begin{bmatrix} v_K^i \\ v_L^i \\ v_E^i \\ v_N^i \\ v_M^i \end{bmatrix} ,$$

$$(i = 1, 2 \ldots n) ,$$

and $\{U^i\}$ are matrices of constant share elasticities, defined above.

Without violating the nonnegativity restrictions on value shares we can set the matrices $\{v^i v^{i\prime} - V^i\}$ equal to zero, for example, by choosing the value shares:

$$\begin{aligned} v_K^i &= 1 , \\ v_L^i &= 0 , \\ v_E^i &= 0 , \\ v_N^i &= 0 , \\ v_M^i &= 0 , \end{aligned}$$

Necessary conditions for the matrices $\{U^i + v^i v^{i\prime} - V^i\}$ to be negative semi-definite are that the matrices of share elasticities $\{U^i\}$ must be negative semi-definite. These conditions are also sufficient, since the matrices $\{v^i v^{i\prime} - V^i\}$ are negative semi-definite for all nonnegative value shares summing to unity and the sum of two negative semi-definite matrices is negative semi-definite.

To impose concavity on the translog price functions the matrices $\{U^i\}$ of constant share elasticities can be represented in terms of the their Cholesky factorizations:

---

[21] The rate of change was introduced by Jorgenson and Lau (1983).

[22] The following discussion of share elasticities with respect to price and concavity follows that of Jorgenson and Lau (1983). Representation of conditions for concavity in terms of the Cholesky factorization is due to Lau (1978).

$$\begin{bmatrix} \beta^i_{KK} & \beta^i_{KL} & \beta^i_{KE} & \beta^i_{KN} & \beta^i_{KM} \\ \beta^i_{KL} & \beta^i_{LL} & \beta^i_{LE} & \beta^i_{LN} & \beta^i_{LM} \\ \beta^i_{KE} & \beta^i_{LE} & \beta^i_{EE} & \beta^i_{EN} & \beta^i_{EM} \\ \beta^i_{KN} & \beta^i_{LN} & \beta^i_{EN} & \beta^i_{NN} & \beta^i_{NM} \\ \beta^i_{KM} & \beta^i_{LM} & \beta^i_{EM} & \beta^i_{NM} & \beta^i_{MM} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \lambda^i_{21} & 1 & 0 & 0 & 0 \\ \lambda^i_{31} & \lambda^i_{32} & 1 & 0 & 0 \\ \lambda^i_{41} & \lambda^i_{42} & \lambda^i_{43} & 1 & 0 \\ \lambda^i_{51} & \lambda^i_{52} & \lambda^i_{53} & \lambda^i_{54} & 1 \end{bmatrix} \begin{bmatrix} \delta^i_1 & 0 & 0 & 0 & 0 \\ 0 & \delta^i_2 & 0 & 0 & 0 \\ 0 & 0 & \delta^i_3 & 0 & 0 \\ 0 & 0 & 0 & \delta^i_4 & 0 \\ 0 & 0 & 0 & 0 & \delta^i_5 \end{bmatrix} \begin{bmatrix} 1 & \lambda^i_{21} & \lambda^i_{31} & \lambda^i_{41} & \lambda^i_{51} \\ 0 & 1 & \lambda^i_{32} & \lambda^i_{42} & \lambda^i_{52} \\ 0 & 0 & 1 & \lambda^i_{43} & \lambda^i_{53} \\ 0 & 0 & 0 & 1 & \lambda^i_{54} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \delta^i_1 & \lambda^i_{21}\delta^i_1 & \lambda^i_{31}\delta^i_1 & \lambda^i_{41}\delta^i_1 & \lambda_{51}\delta^i_1 \\ \lambda^i_{21}\delta^i_1 & \lambda^i_{21}\lambda^i_{21}\delta^i_1+\delta^i_2 & \lambda^i_{21}\lambda^i_{31}\delta^i_1+\lambda^i_{32}\delta_2 & \lambda^i_{41}\lambda^i_{21}\delta^i_1+\lambda^i_{42}\delta_2 & \lambda^i_{51}\lambda^i_{21}\delta^i_1+\lambda^i_{52}\delta_1 \\ \lambda^i_{31}\delta^i_1 & \lambda^i_{31}\lambda^i_{21}\delta^i_1+\lambda^i_{32}\delta^i_2 & \lambda^i_{31}\lambda^i_{31}\delta^i_1+\lambda^i_{32}\lambda^i_{32}\delta^i_2+\delta^i_3 & \lambda^i_{41}\lambda^i_{31}\delta^i_1+\lambda^i_{42}\lambda^i_{32}\lambda^i_2+\lambda^i_{43}\delta^i_3 & \lambda^i_{51}\lambda^i_{31}\delta^i_1+\lambda^i_{52}\lambda^i_{32}\delta^i_2+\lambda_{53}\delta^i_3 \\ \lambda^i_{41}\delta^i_1 & \lambda^i_{41}\lambda_{21}\delta_1+\lambda^i_{42}\delta^i_2 & \lambda^i_{41}\lambda^i_{31}\delta^i_1+\lambda^i_{42}\lambda^i_{32}\delta^i_2+\lambda^i_{43}\delta^i_3 & \lambda^i_{41}\lambda^i_{41}\delta^i_1+\lambda^i_{42}\lambda^i_{42}\delta^i_2+\lambda^i_{43}\lambda^i_{43}\delta^i_3+\delta^i_4 & \lambda^i_{41}\lambda^i_{51}\lambda^i_1+\lambda^i_{42}\lambda^i_{52}\lambda^i_2+\lambda^i_{43}\lambda^i_{53}\delta^i_3+\lambda^i_{54}\delta^i_4 \\ \lambda^i_{51}\delta^i_1 & \lambda^i_{51}\lambda^i_{21}\delta^i_1+\lambda^i_{52}\delta^i_2 & \lambda^i_{51}\lambda^i_{31}\delta^i_1+\lambda^i_{52}\lambda^i_{32}\delta^i_2+\lambda^i_{53}\delta^i_3 & \lambda^i_{41}\lambda^i_{51}\delta^i_1+\lambda^i_{42}\lambda^i_{52}\delta^i_2+\lambda^i_{43}\lambda^i_{53}\delta^i_3+\lambda^i_{54}\delta^i_4 & \lambda^i_{51}\lambda^i_{51}\delta^i_1+\lambda^i_{52}\lambda^i_{52}\delta^i_2+\lambda^i_{53}\lambda^i_{53}\delta^i_3+\lambda^i_{54}\delta^i_4+\delta^i_5 \end{bmatrix}$$

Under constant returns to scale the constant share elasticities satisfy symmetry restrictions and restrictions implied by homogeneity of degree one of the price function. These restrictions imply that the parameters of the Cholesky factorizations $\{\lambda^i_{21}, \lambda^i_{31}, \lambda^i_{41}, \lambda^i_{51}, \lambda^i_{32}, \lambda^i_{42}, \lambda^i_{52}, \lambda^i_{43}, \lambda^i_{53}, \lambda^i_{54}, \delta^i_1, \delta^i_2, \delta^i_3, \delta^i_4, \delta^i_5\}$ must satisfy the following conditions:

$$\begin{aligned} 1 + \lambda^i_{21} + \lambda^i_{31} + \lambda^i_{41} + \lambda^i_{51} &= 0 , \\ 1 + \lambda^i_{32} + \lambda^i_{42} + \lambda^i_{52} &= 0 , \\ 1 + \lambda^i_{43} + \lambda^i_{53} &= 0 , \\ 1 + \lambda^i_{54} &= 0 , \\ \delta^i_5 &= 0 , \end{aligned}$$

$$(i = 1, 2 \ldots n) .$$

Under these conditions there is a one-to-one transformation between the constant share elasticities $\{\beta^i_{KK}, \beta^i_{KL}, \beta^i_{KE}, \beta^i_{KN}, \beta^i_{KM}, \beta^i_{LL}, \beta^i_{LE}, \beta^i_{LN}, \beta^i_{LM}, \beta^i_{EE}, \beta^i_{EN}, \beta^i_{EM}, \beta^i_{NN}, \beta^i_{NM}, \beta^i_{MM}\}$ and the parameters of the Cholesky factorizations. The matrices of share elasticities are negative semi-definite if and only if the diagonal elements $\{\delta^i_1, \delta^i_2, \delta^i_3, \delta^i_4\}$ of the matrices $\{D^i\}$ are non-positive. This completes the specification of our model of production and technical change.

3. Index numbers. The negative of the average rates of technical change in any two points of time, say T and T-l, can be expressed as the difference

between successive logarithms of the price of output, less a weighted average of the differences between successive logarithms of the prices of capital, labor, electricity, nonelectrical energy and materials inputs, with weights given by the average value shares:

$$\begin{aligned}
-\bar{v}_T^i = {} & \ln q_i(T) - \ln q_i(T-1) - \bar{v}_K^i[\ln p_K^i(T) - \ln p_K^i(T-1)] \\
& -\bar{v}_L^i[\ln p_L^i(T) - \ln p_L^i(T-1)] - \bar{v}_E^i[\ln p_E^i(T) - \ln p_E^i(T-1)] \\
& -\bar{v}_N^i[\ln p_N^i(T) - \ln p_N^i(T-1)] - \bar{v}_M^i[\ln p_M^i(T) - \ln p_M^i(T-1)] \ , \\
& \qquad\qquad\qquad\qquad\qquad\qquad (i = 1, 2 \ldots n) \ ,
\end{aligned}$$

where:

$$\bar{v}_T^i = \frac{1}{2}\,[v_T^i(T) + v_T^i(T-1)] \ , \qquad\qquad (i = 1, 2 \ldots n) \ ,$$

and the average value shares in the two periods are given by:

$$\begin{aligned}
\bar{v}_K^i &= \frac{1}{2}\,[v_K^i(T) + v_K^i(T-1)] \ , \\
\bar{v}_L^i &= \frac{1}{2}\,[v_L^i(T) + v_L^i(T-1)] \ , \\
\bar{v}_E^i &= \frac{1}{2}\,[v_E^i(T) + v_E^i(T-1)] \ , \\
\bar{v}_N^i &= \frac{1}{2}\,[v_N^i(T) + v_N^i(T-1)] \ , \\
\bar{v}_M^i &= \frac{1}{2}\,[v_M^i(T) + v_M^i(T-1)] \ , \qquad\qquad (i = 1, 2 \ldots n) \ .
\end{aligned}$$

We refer to the expressions for the average rates of technical change $\{\bar{v}_T^i\}$ as the translog price index of the sectoral rates of technical change.

Similarly, we can consider specific forms for prices of capital, labor, electricity, nonelectrical energy, and materials inputs as functions of prices of individual capital, labor, electricity, nonelectrical energy, and materials inputs into each industrial sector. We assume that the price of each input can be expressed as a translog function of the price of its components. Accordingly, the difference between successive logarithms of the price of the input is a weighted average of differences between successive logarithms of prices of its components. The weights are given by the average value shares of the components. We refer to these expressions of the input prices as translog indexes of the price of sectoral inputs.[23]

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[23] The price indexes were introduced by Fisher (1922). These indexes were first described from the translog price function by Diewert (1976). The corresponding index of technical change was introduced by Christensen and Jorgenson (1970). The translog index of technical change was first derived from the translog price function by Diewert (1980) and by Jorgenson and Lau (1983).

4. Stochastic specification. To formulate an econometric model of production and technical change we add a stochastic component to the equations for the value shares and the rate of technical change. We assume that each of these equations has two additive components. The first is a nonrandom function of capital, labor, electricity, nonelectrical energy, and materials inputs and time; the second is an unobservable random disturbance that is functionally independent of these variables. We obtain an econometric model of production and technical change corresponding to the translog price function by adding random disturbances to all six equations:

$$\begin{aligned}
v_K^i &= \alpha_K^i + \beta_{KK}^i \ln p_K^i + \beta_{KL}^i \ln p_L^i + \beta_{KE}^i \ln p_E^i + \beta_{KN}^i \ln p_N^i + \beta_{KM}^i \ln p_M^i + \beta_{KT}^i \cdot T + \varepsilon_K^i \,, \\
v_L^i &= \alpha_L^i + \beta_{KL}^i \ln p_K^i + \beta_{LL}^i \ln p_L^i + \beta_{LE}^i \ln p_E^i + \beta_{LN}^i \ln p_N^i + \beta_{LM}^i \ln p_M^i + \beta_{LT}^i \cdot T + \varepsilon_L^i \,, \\
v_E^i &= \alpha_E^i + \beta_{KE}^i \ln p_K^i + \beta_{LE}^i \ln p_L^i + \beta_{EE}^i \ln p_E^i + \beta_{EN}^i \ln p_N^i + \beta_{EM}^i \ln p_M^i + \beta_{ET}^i \cdot T + \varepsilon_E^i \,, \\
v_N^i &= \alpha_N^i + \beta_{KN}^i \ln p_K^i + \beta_{LN}^i \ln p_L^i + \beta_{EN}^i \ln p_E^i + \beta_{NN}^i \ln p_N^i + \beta_{NM}^i \ln p_M^i + \beta_{NT}^i \cdot T + \varepsilon_N^i \,, \\
v_M^i &= \alpha_M^i + \beta_{KM}^i \ln p_K^i + \beta_{LM}^i \ln p_L^i + \beta_{EM}^i \ln p_E^i + \beta_{NM}^i \ln p_N^i + \beta_{MM}^i \ln p_M^i + \beta_{MT}^i \cdot T + \varepsilon_M^i \,, \\
v_T^i &= \alpha_T^i + \beta_{KT}^i \ln p_K^i + \beta_{LT}^i \ln p_L^i + \beta_{ET}^i \ln p_E^i + \beta_{NT}^i \ln p_N^i + \beta_{MT}^i \ln p_M^i + \beta_{TT}^i \cdot T + \varepsilon_T^i \,, \\
&\qquad (i = 1, 2 \ldots n) \,,
\end{aligned}$$

where $\{\alpha_K^i, \alpha_L^i, \alpha_E^i, \alpha_N^i, \alpha_M^i, \alpha_T^i, \beta_{KK}^i, \beta_{KL}^i, \beta_{KE}^i, \beta_{KN}^i, \beta_{KM}^i, \beta_{KT}^i, \beta_{LL}^i, \beta_{LE}^i, \beta_{LN}^i, \beta_{LM}^i, \beta_{LT}^i, \beta_{EE}^i, \beta_{EN}^i, \beta_{EM}^i, \beta_{ET}^i, \beta_{NN}^i, \beta_{NM}^i, \beta_{NT}^i, \beta_{MM}^i, \beta_{MT}^i, \beta_{TT}^i\}$ are unknown parameters and $\{\varepsilon_K^i, \varepsilon_L^i, \varepsilon_E^i, \varepsilon_N^i, \varepsilon_M^i, \varepsilon_T^i\}$ are unobservable random disturbances.

Since the value shares sum to unity, the unknown parameters satisfy the same restrictions as before and the random disturbances corresponding to the four value shares sum to zero:

$$\varepsilon_K^i + \varepsilon_L^i + \varepsilon_E^i + \varepsilon_N^i + \varepsilon_M^i = 0 \,, \qquad (i = 1, 2 \ldots n) \,,$$

so that these random disturbances are not distributed independently.

We assume that the random disturbances for all six equations have expected value equal to zero for all observations:

$$E \begin{bmatrix} \varepsilon_K^i \\ \varepsilon_L^i \\ \varepsilon_E^i \\ \varepsilon_N^i \\ \varepsilon_M^i \\ \varepsilon_T^i \end{bmatrix} = 0 \,, \qquad (i = 1, 2 \ldots n) \,.$$

We also assume that the random disturbances have a covariance matrix that is the same for all observations; since the random disturbances corresponding to the five value shares sum to zero, this matrix is positive semi-definite with rank at most equal to five.

We assume that the covariance matrix of the random disturbances corresponding to the first four value shares and the rate of technical change, say Σ^i, has rank five, where:

$$V \begin{bmatrix} \varepsilon_K^i \\ \varepsilon_L^i \\ \varepsilon_E^i \\ \varepsilon_N^i \\ \varepsilon_T^i \end{bmatrix} = \Sigma^i , \qquad (i = 1, 2 \ldots n) ,$$

so the Σ^i is a positive definite matrix. Finally, we assume that the random disturbances corresponding to distinct observations in the same or distinct equations are uncorrelated. Under this assumption that the matrix of random disturbances for the first four value shares and the rate of technical change for all observations has the Kronecker product form:

$$V \begin{bmatrix} \varepsilon_K^i(1) \\ \varepsilon_K^i(2) \\ \vdots \\ \varepsilon_K^i(N) \\ \varepsilon_L^i(1) \\ \vdots \\ \varepsilon_T^i(N) \end{bmatrix} = \Sigma^i \otimes I , \qquad (i = 1, 2 \ldots n) .$$

Since the rates of technical change $\{v_T^i\}$ are not directly observable, the equation for the rate of technical change can be written:

$$-\overline{v}_T^i = \alpha_T^i + \beta_{KT}^i \overline{\ln p_K^i} + \beta_{LT}^i \overline{\ln p_L^i} + \beta_{ET}^i \overline{\ln p_E^i} + \beta_{NT}^i \overline{\ln p_N^i} + \beta_{MT}^i \overline{\ln p_M^i} + \beta_{TT}^i \cdot \overline{T} + \overline{\varepsilon}_T^i , \qquad (i = 1, 2 \ldots n) ,$$

where $\overline{\varepsilon}_T^i$ is the average disturbance in the two periods:

$$\overline{\varepsilon}_T^i = \frac{1}{2} [\varepsilon_T^i(T) + \varepsilon_T^i(T-1)] , \qquad (i = 1, 2 \ldots n) .$$

Similarly, the equations for the value shares of capital, labor, electricity, nonelectrical energy, and materials inputs can be written:

$$\begin{aligned}
\bar{v}_K^i &= \alpha_K^i + \beta_{KK}^i \overline{\ln p_K^i} + \beta_{KL}^i \overline{\ln p_L^i} + \beta_{KE}^i \overline{\ln p_E^i} + \beta_{KN}^i \overline{\ln p_N^i} + \beta_{KM}^i \overline{\ln p_M^i} + \beta_{KT}^i \cdot \bar{T} + \bar{\varepsilon}_K^i ,\\
\bar{v}_L^i &= \alpha_L^i + \beta_{KL}^i \overline{\ln p_K^i} + \beta_{LL}^i \overline{\ln p_L^i} + \beta_{LE}^i \overline{\ln p_E^i} + \beta_{LN}^i \overline{\ln p_N^i} + \beta_{LM}^i \overline{\ln p_M^i} + \beta_{LT}^i \cdot \bar{T} + \bar{\varepsilon}_L^i ,\\
\bar{v}_E^i &= \alpha_E^i + \beta_{KE}^i \overline{\ln p_K^i} + \beta_{LE}^i \overline{\ln p_L^i} + \beta_{EE}^i \overline{\ln p_E^i} + \beta_{EN}^i \overline{\ln p_N^i} + \beta_{EM}^i \overline{\ln p_M^i} + \beta_{ET}^i \cdot \bar{T} + \bar{\varepsilon}_E^i ,\\
\bar{v}_N^i &= \alpha_N^i + \beta_{KN}^i \overline{\ln p_K^i} + \beta_{LN}^i \overline{\ln p_L^i} + \beta_{EN}^i \overline{\ln p_E^i} + \beta_{NN}^i \overline{\ln p_N^i} + \beta_{NM}^i \overline{\ln p_M^i} + \beta_{NT}^i \cdot \bar{T} + \bar{\varepsilon}_N^i ,\\
\bar{v}_M^i &= \alpha_M^i + \beta_{KM}^i \overline{\ln p_K^i} + \beta_{LM}^i \overline{\ln p_L^i} + \beta_{EM}^i \overline{\ln p_E^i} + \beta_{NM}^i \overline{\ln p_N^i} + \beta_{MM}^i \overline{\ln p_M^i} + \beta_{MT}^i \cdot \bar{T} + \bar{\varepsilon}_M^i ,\\
& \qquad (i = 1, 2 \ldots n) .
\end{aligned}$$

where:

$$\begin{aligned}
\bar{\varepsilon}_K^i &= \tfrac{1}{2} [\varepsilon_K^i(T) + \varepsilon_K^i(T-1)] ,\\
\bar{\varepsilon}_L^i &= \tfrac{1}{2} [\varepsilon_L^i(T) + \varepsilon_L^i(T-1)] ,\\
\bar{\varepsilon}_E^i &= \tfrac{1}{2} [\varepsilon_E^i(T) + \varepsilon_E^i(T-1)] ,\\
\bar{\varepsilon}_N^i &= \tfrac{1}{2} [\varepsilon_N^i(T) + \varepsilon_N^i(T-1)] ,\\
\bar{\varepsilon}_M^i &= \tfrac{1}{2} [\varepsilon_M^i(T) + \varepsilon_M^i(T-1)] , \qquad (i = 1, 2 \ldots n) .
\end{aligned}$$

As before, the average value shares $\{\bar{v}_K^i, \bar{v}_L^i, \bar{v}_E^i, \bar{v}_N^i, \bar{v}_M^i\}$ sum to unity, so that the average disturbances $\{\bar{\varepsilon}_K^i, \bar{\varepsilon}_L^i, \bar{\varepsilon}_E^i, \bar{\varepsilon}_N^i, \bar{\varepsilon}_M^i\}$ sum to zero:

$$\bar{\varepsilon}_K^i + \bar{\varepsilon}_L^i + \bar{\varepsilon}_E^i + \bar{\varepsilon}_N^i + \bar{\varepsilon}_M^i = 0 , \qquad (i = 1, 2 \ldots n) .$$

The covariance matrix of the average disturbances corresponding to the equation for the rate of technical change for all observations, say Ω, is a Laurent matrix:

$$V \begin{bmatrix} \bar{\varepsilon}_T^i(2) \\ \bar{\varepsilon}_T^i(3) \\ \vdots \\ \bar{\varepsilon}_T^i(N) \end{bmatrix} = \Omega ,$$

where:

$$\Omega = \begin{bmatrix} \frac{1}{2} & \frac{1}{4} & 0 & \ldots & 0 \\ \frac{1}{4} & \frac{1}{2} & \frac{1}{4} & \ldots & 0 \\ 0 & \frac{1}{4} & \frac{1}{2} & \ldots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \ldots & \frac{1}{2} \end{bmatrix} .$$

The covariance matrix of the average disturbance corresponding to each equation for the four value shares is the same, so that the covariance matrix of the average disturbances for the first four value shares and the rate of technical change for all observations has the Kronecker product form

$$V \begin{bmatrix} \bar{\varepsilon}^i_K(2) \\ \bar{\varepsilon}^i_K(3) \\ \vdots \\ \bar{\varepsilon}^i_K(M) \\ \bar{\varepsilon}^i_L(2) \\ \vdots \\ \bar{\varepsilon}^i_T(N) \end{bmatrix} = \Sigma^i \otimes \Omega , \qquad (i = 1, 2 \ldots n) .$$

5. Estimation. Although disturbances in equations for the average rate of technical change and the average value shares are autocorrelated, the data can be transformed to eliminate the autocorrelation. The matrix Ω is positive definite, so that there is a matrix T such that:

$$T\Omega T' = I \quad ,$$
$$T'T = \Omega^{-1} .$$

To construct the matrix T we can first invert the matrix Ω to obtain the inverse matrix Ω^{-1}, a positive definite matrix We then calculate the Cholesky factorization of the inverse matrix Ω^{-1},

$$\Omega^{-1} = LDL' ,$$

where L is a unit lower triangular matrix and D is a diagonal matrix with positive elements along the main diagonal. Finally, we can write the matrix T in the form:

$$T = D^{1/2}L' ,$$

where $D^{1/2}$ is a diagonal matrix with elements along the main diagonal equal to the square roots of the corresponding elements of D.

We can transform the equations for the average rates of technical change by the matrix $T = D^{1/2}L'$ to obtain equations with uncorrelated random disturbances:

$$D^{1/2}L'\begin{bmatrix}\bar{v}_T^i(2)\\ \bar{v}_T^i(3)\\ \vdots\\ \bar{v}_T^i(N)\end{bmatrix} = D^{1/2}L'\begin{bmatrix}1 & \overline{\ln p_K^i}(2) & \dots & 2-\frac{1}{2}\\ 1 & \overline{\ln p_K^i}(3) & \dots & 3-\frac{1}{2}\\ & \vdots & & \\ 1 & \overline{\ln p_K^i}(N) & \dots & N-\frac{1}{2}\end{bmatrix}\begin{bmatrix}\alpha_T^i\\ \beta_{KT}^i\\ \vdots\\ \beta_{TT}^i\end{bmatrix} + D^{1/2}L'\begin{bmatrix}\bar{\varepsilon}_T^i(2)\\ \bar{\varepsilon}_T^i(3)\\ \vdots\\ \bar{\varepsilon}_T^i(N)\end{bmatrix},$$

$$(i = 1, 2 \dots n),$$

since:

$$T\Omega T' = (D^{1/2}L')\,\Omega\,(D^{1/2}L')' = I$$

The transformation T = $D^{1/2}L'$ is applied to data on the average rates of technical change $\{\bar{v}_T^i\}$ and data on the average values of the variables that appear on the right hand side of the corresponding equations.

We can apply the transformation T = $D^{1/2}$ L' to the first four equations for average value shares to obtain equations with uncorrelated disturbances. As before, the transformation is applied to data on the average values shares and the average values of variables that appear in the corresponding equations. The covariance matrix of the transformed disturbances from the first four equations for the average value shares and the equation for the average rate of technical change has the Kronecker product form:

$$(I \otimes D^{1/2}L')(\Sigma^i \otimes \Omega)(I \otimes D^{1/2}L')' = \Sigma^i \otimes I, \quad (i = 1, 2 \dots n).$$

To estimate the unknown parameters of the translog price function we combine the first four equations for the average value shares with the equation for the average rate of technical change to obtain a complete econometric model of production and technical change. We estimate the parameters of the equations for the remaining average value shares, using the restrictions on these parameters given above. The complete model involves twenty unknown parameters. A total of twenty-two additional parameters can be estimated as functions of these parameters, given the restrictions. restrictions. Our estimates of the unknown parameters of thee econometric model of production and technical change will be based on the nonlinear three-stage least squares estimator introduced by Jorgenson and Laffont.[24]

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[24] See Jorgenson and Laffont (1974).

Appendix D

Excerpts From an Analysis of the Expected Impact of Various Electrotechnologies on Electricity Demand

The following material identifies various electrotechnologies that may affect electricity use from the present to the year 2000. The material considers separately certain industrial, commercial, residential, and transportation applications and comments on their timing and impact.

TERMS USED IN THE TABLES

Particular terms used in the tables are explained below.

Technology: New electrotechnologies or improvements in existing electrotechnologies that can be expected to make an impact on electricity consumption.

Market Pull: Time in which technology becomes marketable, requiring no subsidization or major research and development for market acceptance. Conceptually, this is the first major upward inflection on a market penetration "S" curve. Timing of market pull stages is classified as follows:

Near Term	1984 to 1989
Mid-Term	1990 to 1995
Long Term	1996 to 2000
Distant Future	beyond 2000 or never.

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* Excerpted by permission from O. Zimmerman and A. Faruqui, Electrotechnologies—Impact on Electric Demand: Selected Applications in the Residential, Commercial, Industrial, and Electric Transportation Sectors. Palo Alto, California: Electric Power Research Institute. Internal Report. August 21, 1984.

Impact (Table D-1): Change in electricity consumption for the technology relative to 1980 consumption, measured in megawatt hours (MWh), for years 1990 and 2000.

Relative Impact (Table D-1): Increase in a specific technology's electricity consumption in the year 2000 is classified as follows:

Small	less than or equal to 1-percent increase over 1980 consumption
Moderate	greater than 1-percent and less than 10-percent increase over 1980 consumption
Significant	equal to or greater than 10-percent increase over 1980 consumption.

Impact (Tables D-2, D-3, and D-4): Expected impact on electricity consumption in years 1990 and 2000 relative to current consumption is classified as follows:

Small	less than or equal to 1-percent change relative to existing end use or class load, as appropriate
Moderate	greater than 1-percent and less than 10-percent change relative to existing end use or class load, as appropriate
Significant	equal to or greater than 10-percent change relative to existing end use or class load, as appropriate.

NOTE: Impacts are assessed from a national perspective. Some technologies may have significant utility or regional impacts with only moderate or insignificant national impacts.

Impact Type (Tables D-2, D-3, and D-4): Classified as follows:

D peak demand affected more than total kilowatt hours
E total kilowatt hours affected more than peak demand
B proportional demand/energy impact.

TABLE D-1 -Effects of Using Some Electrotechnologies in Industrial Applications[a]

		Impact on Electricity Consumption (MWh)		Impact on Electricity Use in 2000 Relative to Base Period (1980)	
Technology	"Market Pull" Stage	1990	2000		Comments
MATERIALS PRODUCTION					
Direct are melting	Near term	+ 8,900	+ 14,900	Significant	Reduced production and capital costs Increased productivity Reduced environmental impacts
Direct resistance melting	Near term	+ 750	+ 1,440	Significant	Increased energy efficiency Reduced environmental impacts
Induction melting	Near term	+ 12,600	+ 28,400	Significant	Lower production costs Reduced environmental impacts
Plasma processing	Mid-term	+ 3,600	+ 21,400	Significant	Lower capital and production costs Increased energy efficiency Shift from petroleum and gas to coal feedstock
METALS FABRICATION					
Electrical discharge and electrochemical machining	Near term	+ 200	+ 1,100	Significant	
Electron beam heating	Mid-term	+ 100	+ 300	Significant	Increased energy efficiency Higher capital costs Lower production costs
Induction heating	Near term	+ 15,800	+ 31,500	Significant	Increased energy efficiency Higher capital costs Lower production costs Lower labor requirements

		Impact on Electricity Consumption (MWh)		Impact on Electricity Use in 2000 Relative to Base Period (1980)	
Technology	"Market Pull" Stage	1990	2000		Comments
METALS FABRICATION (cont.)					
Laser processing	Near term	+ 22	+ 110	Significant	Increased productivity and additional manufacturing opportunities
Flexible manufacturing	Hear term	+ 2,160	+ 26,400	Significant	Increased productivity Improved work environment Job displacement and shift in required skills
PROCESS RELATED					
Adjustable-speed air-conditioner drives	Near term	+ 224,000	+ 470,000	Significant	
Electrolytic separation and electrochemical synthesis	Near term	+ 5,800	+ 12,700	Significant	
Heat pumps and mechanical vapor recompression	Hid-term	+ 1,100	+ 5,900	Significant	
Infrared drying and curing	Near term	+ 1,500	+ 3,900	Significant	
Microwave heating and drying	Mid-term	+ 600	+ 2,700	Significant	Higher capital cost Lower labor requirements Improved work environment
DEMAND CONTROL					
Electromagnetic sensors					Application captured in commercial matrix
Homeostatic control	Long term			Small	Requires widespread adoption of homeostatic rates

[a] Terms in the table are explained further in the text.

TABLE D-2 Effects of Using Some Electrotechnologies in Commercial Applications

		Impact on Electricity Consumption (MWh)			
Technology	"Market Pull" Stage	1990	2000	Type	Comments
SPACE CONDITIONING					
Heat pump—30% improvement in air source efficiency	Near term	Moderate	Significant	B	Enhanced efficiency will accelerate acceptance Extremely high fuel-switching potential
Heat pump—earth coupled including open and closed loopgh	Near term	Small	Moderate	B	High per-unit potential Overall penetration limited by availability of water or earth coil location
Storage air conditioning	Near term	Moderate	Significant	D	Market is growing at present arid several utilities are promoting Cost-effectiveness and customer acceptance are improving Rate mechanisms are already in place
LIGHTING					
New electric ballast	Near term	Moderate	Significant	B	Provides a savings of 25 billion KWh per year [b]
New improved source and level controls	Near term	Moderate	Significant	B	
WATER HEATING					
Heat pump water heater	Near term	Moderate	Significant	B	Commercial penetration and fuel-switching potential greater than in those for residential uses
Heat recovery water heating air conditioning, heat pump, or refrigeration	Near term	Moderate	Significant	B	More applicable and more cost-effective for commercial than residential uses

		Impact on Electricity Consumption			
Technology	"Market Pull" Stage	1990	2000	Type	Comments
OFFICE AUTOMATION DEMAND CONTROL					
Electromagnetic sensors (EMS)	Near term	Moderate	Significant	B	A high percentage of new buildings are being equipped with EMS, and building retrofit for EMS is increasing
Homeostatic control	Long term	Small	Small	B	Impact determined by the probability of homeostatic rate adoption Requires real-time communication with each meter Adoption in commercial class will first appear in very large concentration of heating, ventilation, and air conditioning loads

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[a] Terms in the table are explained further in the text.

[b] EPRI Journal, June 1982.

TABLE D-3 Effects of Using Some Electrotechnologies in Residential Applications[a]

		Impact on Electricity Consumption			
Technology	"Market Pull" Stage	1990	2000	Type	Comments
SPACE CONDITIONING					
Heat pumps--30% improvement in air source efficiency	Near term	Moderate	Significant	B	Enhanced efficiency will accelerate customer acceptance and penetration of air source heat pump Extremely high fuel-switching potential
Heat pumps--earth coupled including open and closed loop	Near term	Small	Moderate	B	High per-unit savings potential and high fuel-switching potential Overall penetration limited by system cost and land and water limitations
Heat pumps--add-on air-to-air with fossil backup	Near term	Moderate	Moderate	E	May have fuel-switching potential Application is primarily limited to retrofitting existing fossil systems Highly-rate sensitive Utility efforts to promote such heat pumps are only moderately successful
Dual-fuel heating—fully sized fossil and electric systems	Near term	Small	Moderate	E	Most of its impact results from fuel switching Applicability is region-specific and depends on rate incentives
Storage space heating—new storage medium with 40% cost reduction	Mid-term	Small	Moderate	D	Significant impact on per-unit demand Projected cost reductions will significantly enhance cost-effectiveness and penetration Application will be limited to high heating load areas and to willingness of utilities to provide rate incentives

		Impact on Electricity Consumption			
Technology	"Market Pull" Stage	1990	2000	Type	Comments
WATER HEATING					
Heat pump water heater	Near term	Small	Moderate	B	Requires 20% market penetration before deemed significant
Heat recovery water heating (air conditioning or heat pump)	Near-term	Small	Small	B	Market penetration and impact potential limited to a few geographic regions regions with significant cooling load
DEMAND CONTROL					
Direct utility load control	Near term	Small	Moderate	D	
Distributed control	Mid-term	Small	Moderate	B	Distributed control (vs direct or local control) has the potential to be the dominant form of load control The impact of control depends on penetration
Local control	Near term	Small	Small	B	Requires rate incentives (e.g., depending on demand, time of day, or load factor) The impact of control depends on penetration

[a] Terms in the table are explained further in the text.

TABLE D-4 Effects of Using Some Electrotechnologies in Transportation Applications[a]

		Impact on Electricity Consumption			
Technology	"Market Pull" Stage	1990	2000	Type	Comments
ELECTRIC VEHICLES					
100% improvement in lead acid battery life without increasing mass	Mid-term	Moderate	Small	E	Advanced Beta Battery expected to compete for year 2000 impact
Advanced Beta Battery with triple life	Long term	Small	Significant	E	

[a] Terms in the table are explained further in the text.

Glossary

BF:	Blast furnace
BOF:	Basic oxygen furnace
Btu:	British thermal unit(s)
CPI:	Consumer price index
DOE/EIA:	U.S. Department of Energy/Energy Information Administration
DPI:	Disposable private income
DRI:	Direct-reduced iron
ECAR:	East Central Area Reliability Coordination Agreement
EEI:	Edison Electric Institute
Electricity intensity:	Electric energy per unit of economic output, e.g., kilowatt hours per dollar
Electrification:	The adoption of processes and activities based on the use of electricity
EPRI:	Electric Power Research Institute
ERCOT:	Electric Reliability Council of Texas
GNP:	Gross national product
GPO:	Gross product originating
GW:	Gigawatt (s)
GWh:	Gigawatt hour(s)
kW:	Kilowatt(s)
kWh:	Kilowatt hour(s)
MAAC:	Mid-Atlantic Area Council
MAIN:	Mid-America Interpool Network

MAPP:	Mid-Continent Area Power Pool
MIT:	Massachusetts Institute of Technology
MW:	Megawatt(s)
MWh:	Megawatt hour(s)
NAS:	National Academy of Sciences
NBECS:	National Building Energy Consumption Survey
NERC:	National Electric Reliability Council
NPCC:	Northeast Power Coordinating Council
OECD:	Organisation for Economic Co-operation and Development
OPEC:	Organization of Petroleum Exporting Countries
OTA:	Office of Technology Assessment, U.S. Congress
PG&E:	Pacific Gas and Electric Company
PPI:	Producer price index
Productivity:	Output per unit of input
PURPA:	Public Utility Regulatory Policies Act
SERC:	Southeastern Electric Reliability Council
Slope:	The ratio of vertical change to horizontal change in going along a line. Slope measures the steepness with which a line is inclined to the horizontal axis
SPP:	Southwest Power Pool
USEIA:	U.S. Energy Information Administration
W:	Watt(s)
WSCC:	Western Systems Coordinating Council