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ENERGY AND ECONOMIC GROWTH

A STUDY

PREPARED FOR THE USE OF THE

SUBCOMMITTEE ON ENERGY

OF THE

JOINT ECONOMIC COMMITTEE
CONGRESS OF THE UNITED STATES

AUGUST 31, 1977

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LETTERS OF TRANSMITTAL

AUGUST 26, 1977.

To the Members of the Joint Economic Committee:

Transmitted herewith for the use of the Joint Economic Committee and other Members of Congress is a study done at the request of the Subcommittee on Energy entitled "Energy and Economic Growth," prepared by Marc H. Ross and Robert H. Williams.

This study is one of a series prepared to commemorate the thirtieth anniversary of the Employment Act of 1946. In the course of this review the Committee and its Subcommittees have examined a wide range of problem areas in an attempt to develop improved means to achieve the goals of this act. Other studies focus on employment, inflation, economic growth, monetary and fiscal policies, and economic planning, among other issues.

Sincerely,

RICHARD BOLLING,
Chairman, Joint Economic Committee.

AUGUST 23, 1977.

Hon. RICHARD BOLLING,
Chairman, Joint Economic Committee, Congress of the United States, Washington, D.C.

DEAR MR. CHAIRMAN: I am pleased to transmit herewith a study prepared for the Subcommittee on Energy entitled "Energy and Economic Growth." This study was written by Marc H. Ross, professor of physics at the University of Michigan, and Robert H. Williams of the Center for Environmental Studies, Princeton University.

Ross and Williams show that current economic and demographic trends will yield a marked decline in energy consumption growth in the future due to slower labor force growth and the steady shift from energy-intensive to less energy-intensive goods and services. These trends could cut energy growth from its level of 4 percent annually for the years, 1960 to 1973, to less than 2.5 percent from 1985 to 2000.

After examining these trends, the authors show that very large efficiency improvements could be made in current energy-using processes. Reductions in fuel consumption of over 40 percent are possible. Four areas account for 60 percent of the total savings potential: Space heating and cooling, water heating, the automobile, and cogeneration of steam and electricity at industrial sites. If fully realized, according to Ross and Williams, these technical improvements could hold the growth in energy use in the United States close to zero from 1985 to 2000. This country is in a better position than many countries to reduce its energy consumption growth because of the waste in our current patterns of use.

Also, Ross and Williams contend that the obstacles facing adoption of new conservation technologies are primarily institutional rather than technical or economic. Strong policies aimed at fostering the use of life-cycle cost comparisons and easier access to credit for conservation investments will be vital to realizing the potential savings.

The findings of this study, of course, are those of the authors and do not necessarily coincide with the views of the members of the Subcommittee on Energy.

Sincerely,

EDWARD M. KENNEDY,
Chairman, Subcommittee on Energy.

CONTENTS

ENERGY AND ECONOMIC GROWTH

By **M. H Ross* and R. H. Williams****

I. SUMMARY AND CONCLUSIONS

It is becoming increasingly difficult to sustain a high rate of energy growth to support economic growth in the United States, on account of the constraining effects of higher energy prices, diminishing domestic supplies of oil and gas, our growing dependence on insecure foreign oil, and worsening energy—environmental problems. Fortunately, it is feasible to maintain a healthy economy with much slower energy growth than we have had in the past. It is the purpose of this paper to show how this might be achieved.

In part slower energy growth in the future will result from underlying trends that have little to do with present energy problems. GNP growth can be expected to slow down significantly in the last two decades of this century because of established demographic trends. Moreover, the economy is evolving toward less energy-intensive activities. The mix of economic activity can be expected to continue shifting from goods to services, and in the goods sector from energy-intensive primary materials processing to materials fabrication activities. In sections II.C and II.D we examine these established trends and conclude that their continuation probably would lead to an energy growth rate of only about 2.3 percent per year from 1985 to 2000, down from about 3 percent over the past 25 years, or 4 percent over the period 1960–1973.

This analysis of historical trends does not include the effect of rising energy prices and the opportunities for increasing the efficiency of energy use throughout the economy. The extent of this opportunity is suggested by the fact discussed in section III that heavily industrialized Western European nations with per capita incomes comparable to those in the U.S. have energy-GNP ratios about two-thirds the U.S. level. In this sense the U.S., which has been especially extravagant in its use of energy, is in a better position than most other nations to relieve the impact of the "new energy realities," because this inefficient use constitutes a large "resource base" for fuel conservation.

In section IV.C we estimate that a reduction in fuel consumption of over 40 percent is possible through technical improvements in today's economy, that is, through reduction in specific energy, the energy consumed per unit of a good or service sold to a consumer. Four areas account for 60 percent of the total savings potential: Space con-

*Mr. Ross is professor of physics at the University of Michigan.
**Mr. Williams is research scientist at Princeton University's Center for Environmental Studies and was supported in this work by a grant from the Max and Anna Levinson Foundation.

ditioning, water heating, the automobile, and the "cogeneration" of steam and electricity at industrial sites. The last mentioned technology is a modern version of a fuel saving technique long in use in Europe and, to a more limited degree, in this country. As discussed in section IV.D, most of the shift to electricity needed across the economy could be provided via this fuel conserving technology.

If the present fuel savings potential were realized over the remainder of this century—23 years—the E/GNP ratio would decline 2.3 percent per year faster than the historically projected rate during that period. Since with "historical growth" conditions energy consumption would be growing at 2.3 percent per year in the period 1985 to 2000, the net effect of pursuing these technical improvements would be zero growth in energy consumption in this period. Opportunities involving substantial technological innovation are not reflected in this estimate; pursuit of technical change would enable a continuation of zero energy growth, or even negative energy growth, for a period near the turn of the century and beyond.

The wide use of energy conservation devices and materials would probably spur productivity gains in the economy as a whole. Efforts to save energy in space heating, for example, could create a demand for millions of heat pumps. The scale of this and most other conservation devices is well suited for technological improvement through competitive trials and cost cutting through mass production. The second law efficiency concept we have used here is an index which suggests that these productivity gains could be pursued for decades, because the very low efficiencies for most energy-consuming technologies today show that we are a long way from technological limits. This is in sharp contrast to the situation with major energy supply technologies. We show that in the case of central-station electric power generation, as an example, opportunities for cost cutting through continued technical change and continued pursuit of scale economies are much more limited.

A determined national effort aimed at reducing energy inefficiency would also create many new job opportunities. New businesses and industries would be needed to produce, market, install, maintain, and repair energy conservation technology: new building insulation materials, heat pumps, electronic controls for regulating energy use in buildings, new types of batteries and other local energy storage systems, new coal-burning cogeneration devices, retrofit equipment for large air-conditioning systems, communications systems that substitute for transportation, and so on.

Producing the new equipment needed for this conservation program would constitute a major economic effort—the investment of hundreds of billions of dollars over the next decade or so. But this program would be less costly than developing the corresponding energy supply capacity.

The constraints facing very extensive implementation of energy conservation technology are primarily institutional, and not technological or economic. A number of existing arrangements inhibit investment in conservation: Forms of utility regulation, special tax incentives for capital investment in energy supply, and fuel price controls. In addition much energy conservation investment is intrinsically more difficult to manage than corresponding supply investments, because of the large number of decisionmakers that are usually involved. However, some very imaginative policy proposals are being advanced to cope with these problems within the framework of present market practices. But rapid and wide scale implementation of energy conservation technology will not be possible without a coherent national energy policy aimed at facilitating conservation measures such as those we set forth in this paper.

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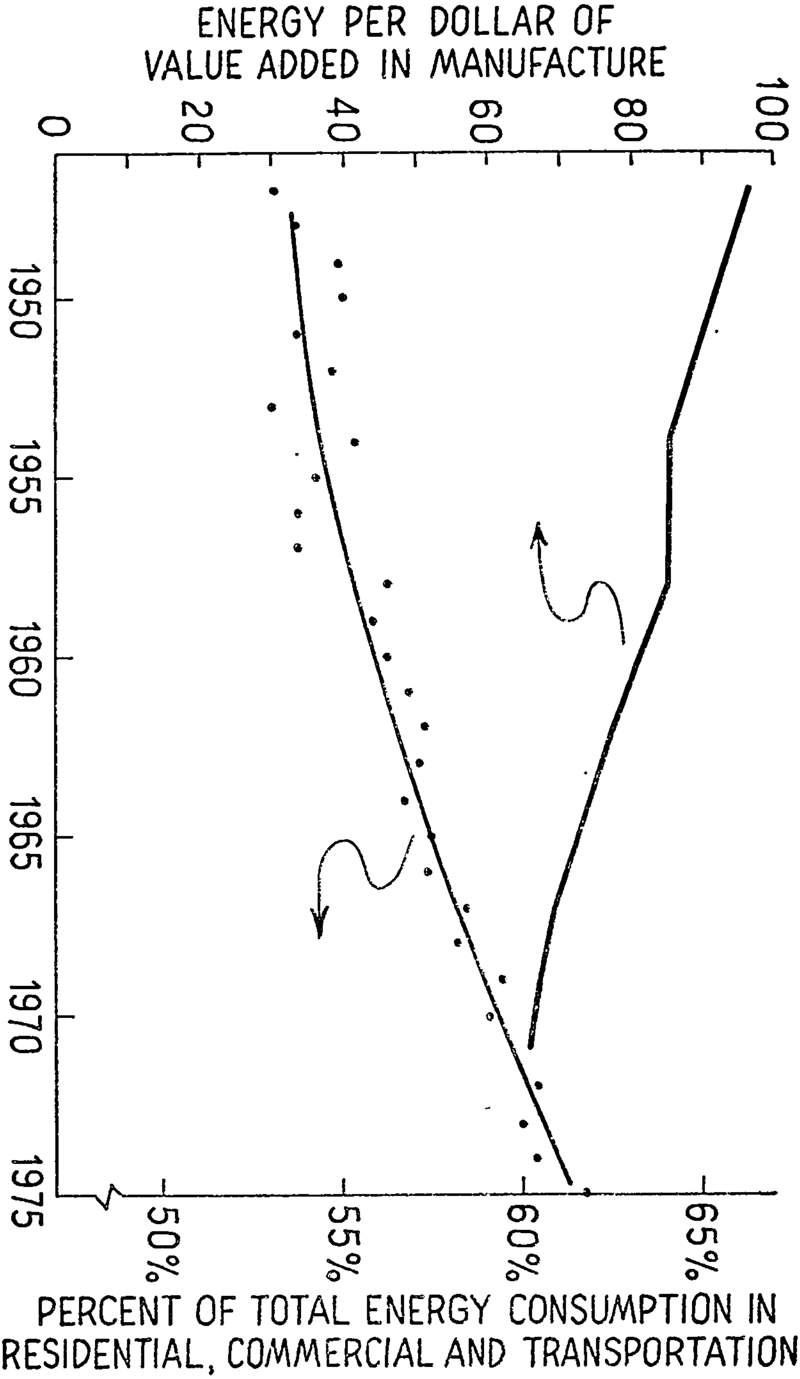
II. THE RELATIONSHIP BETWEEN ENERGY CONSUMPTION AND GROSS NATIONAL PRODUCT

A. Introduction

The last two or three decades have been a period of dynamic change in the U.S. economy, accompanied by significant changes in the patterns of energy use. In the manufacturing sector there has been more growth in the fabricating industries and less growth in the energy intensive basic materials industries than in previous decades. More generally there has been a shift in emphasis from goods to service-producing industries. These shifts in economic activity have been accompanied by a shift in the mix of energy consumption, with a declining manufacturing share compensated by a steadily increasing share of overall energy use in the commercial, residential, and transportation sectors. (See figure 1.) Despite such dynamic change the growth patterns for overall energy consumption and gross national product have been remarkably similar: Depending on the time interval chosen for comparison one finds total energy consumption growing at about the same rate as real GNP or only a few tenths of a percentage point more slowly than GNP. Both GNP—in constant dollars—and energy consumption have displayed total growth rates in the range of 3 to 4 percent. (See figure 2.)

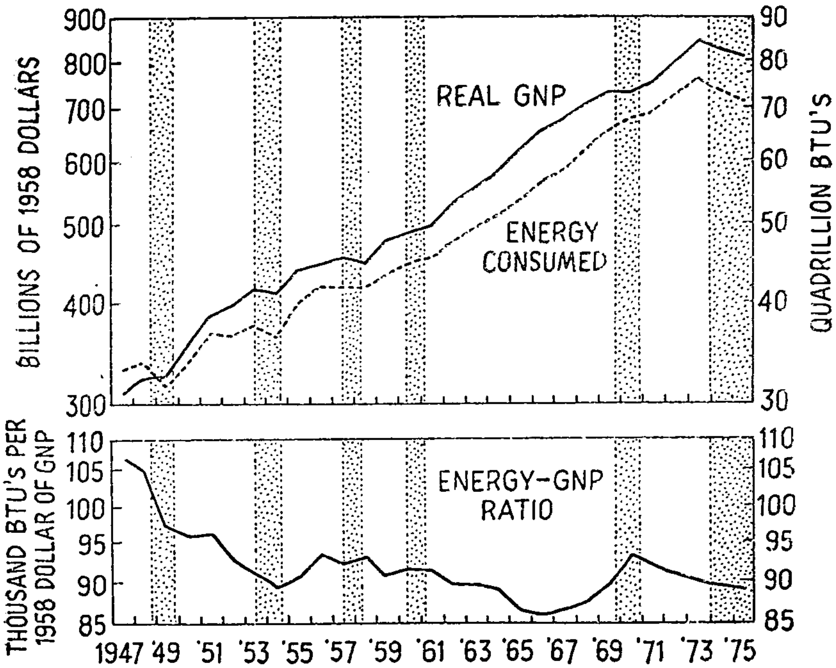
FIGURE 1.—The residential, commercial, and transportation sectors have been taking an increasing fraction of total energy consumption. Energy consumed in manufacturing per dollar of value added (1,000 Btu per 1967 dollar) showed a substantial decline during this period of level or falling energy prices. Value added is adjusted to remove effects of inflation using a deflator appropriate to manufactured goods.

FIGURE 1.—Continued.



Sources: U.S. Bureau of Mines Minerals Yearbooks and press releases, and references 8 and 20.

FIGURE 2.—Energy consumption, real gross national product and their ratio in the U.S., 1947–1975. The shaded periods represent recessions.



Sources: Reference 6 and Bureau of Mines press releases.

Many analysts and policymakers have argued that this close historical relationship between aggregate energy use and economic product implies that economic growth will falter if energy consumption cannot continue to grow or if it grows more slowly than it has in the past.[1] This argument has some validity when there are sudden changes in energy prices and fuel availability, as in the 1973–74 energy crisis. But the argument ignores the fact that during the recent decades of relatively constant E/GNP, low and stable or declining energy prices stimulated increasing energy use, and it ignores the potential impacts of recent large price increases and likely continued price increases on the evolution of energy consumption patterns. As remarked recently:[2]

> One can imagine many uses for which an extrapolation of past aggregate behavior would be adequate. The central question here is whether it is adequate for predicting crucial turning points in the trend * * *. A projection ignoring (changes in important parameters) amounts to what is termed a forecast of "persistence" in weather forecasting. Persistence means simply that the weather experienced presently is forecast to continue into the next period. The method is the more reliable the shorter the forecast period in relation to the typical time scale for significant weather changes, and for most locations in this country it is easy to be right about 80 percent of the time on short-range forecasts. Unfortunately one misses every turning point * * *.

Extrapolation of past aggegate trends in energy consumption is an inappropriate method of making energy projections for the new era of energy we are entering, when we can expect limits on the availability of particular fuel forms such as natural gas, dramatic energy price increases, and new Government initiatives designed to influence energy consumption patterns so as to mitigate the impacts of these new constraints.

It is our thesis that there are substantial opportunities for uncoupling energy growth from economic growth in the present economy, so that a major reduction in projected future energy consumption levels can be achieved without major dislocations or sacrifice of economic growth. In this paper we develop this thesis, through an examination of underlying economic and technological factors relating to the evolution of the U.S. economy. Here we are concerned with an intermediate time scale for the economy, extending from the early 1980's out to the turn of the century. We will not explore short-term responses of the economy to "energy crises" or the possible behavior of the economy some 50 years in the future when the role of energy and other resource inputs in the economy may be very different.

The basic points we wish to make are (*a*) that over recent decades efficiency in the use of energy has been a minor concern in many activities because energy prices were low and stable or declining, (*b*) that rising energy prices now provide incentives to exploit truly enormous opportunities for saving energy through technical changes, and (*c*) that some relatively minor changes in "the rules," i.e., in policies relating to energy, can lead to a robust economy with greatly diminished and perhaps zero growth in aggregate energy consumption.

Energy efficiency has not been a minor concern in all sectors of the economy. In the basic materials processing industries (primary metals, chemicals, pulp and paper, glass, cement, etc.), there has been a continuing effort to improve energy efficiency through process modernization, even during the recent decades of stable or declining energy prices. The steel industry for instance, is continuing a long-term trend of investment in new processes such as the basic oxygen furnace, continuous casting, and increased use of scrap. Among other benefits, such innovations are leading to reduced fuel requirements for producing a ton of steel. In the period 1947–69 the average fuel requirements for raw steel production fell from 33.5 to 24.6 million Btu's per ton.[3] A continuation of this modernization process was projected in 1971 (before the "energy crisis") to result in a further 17-percent savings by 1980, [4] while a 30-percent fuel savings per ton relative to 1969 performance would result if the entire industry were brought up to modern standards.[5]

Similar innovations have led to reduced electricity requirements for producing aluminum, from 9.1 kWh per pound of aluminum in 1947 to 8.2 kWh per pound in 1971. An Alcoa smelting process recently developed requires only 5 kWh per pound.[3]

In energy-intensive industries like these, energy has accounted for much more than the 4 to 5 percent of total manufacturing input costs characteristic of manufacturing overall, so that even when energy prices were low there was a strong incentive to use energy efficiently. The decline in the ratio of energy consumption to value added in manufacturing overall during the period 1947–71 (figure 1)[3] while the price paid for energy in manufacturing (in constant dolllars) also was declining, reflects this trend toward greater efficiency in energy-intensive manufacturing activities. This trend might well accelerate now that energy prices are rising.

While continued and perhaps accelerated efficiency improvements in energy-intensive industries will contribute to an overall reduction in the growth of energy consumption, the greatest opportunities for energy savings lie in other areas toward which the economy has been evolving. As mentioned earlier, the mix of manufacturing activity has been shifting from basic materials production toward fabrication, and economic activity generally has been shifting from production of goods to production of services. There was also a rapid increase in energy use in residences, in passenger travel, and in commercial buildings in the 1950's and 1960's, which should be obvious to any casual observer. One important characteristic of the latter shift is that, in contrast to the attention given in the past to energy efficiency in the design of processes for energy-intensive manufacturing, little attention generally has been given to efficiency in the design of these activities. In these areas there has been a general tendency toward increased "specific energy" use along with the rapid growth in the activity itself.

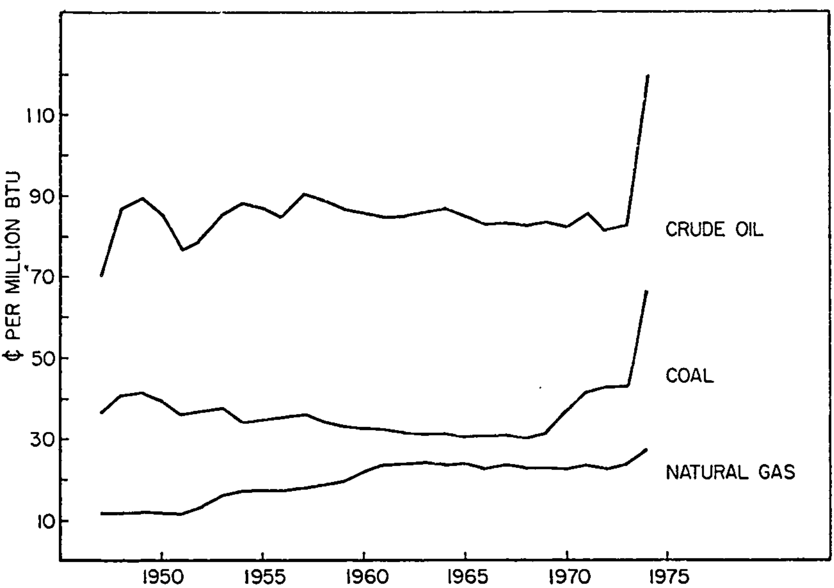
Specific energy is defined as the energy consumption per unit of product. Examples of specific energies are the energy consumption in a building per square foot of floor area; the energy use per mile of auto travel; and the energy use associated with any product per dollar of total cost. Energy consumption in buildings has steadily increased, reflecting trends toward increased lighting, air-conditioning, window area, etc. Buildings in New York City constructed in the late 1960's require about twice as much energy per square foot as buildings constructed in the early 1950's. [9] In this period, there also was a gradual deterioration of automotive fuel economy as we moved to bigger cars with power equipment, air-conditioning, etc. Similarly, fuel requirements per passenger mile in air transport roughly doubled as the transition from propeller- to jet-driven aircraft tool place. [10] When technological changes were made in such areas to increase comfort or convenience, little consideration was given to energy efficiency. But there are important technical improvements which in most cases will enable essentially the same amenities to be enjoyed at no greater cost and with much lower fuel consumption. Here we are not talking about voluntary "remedial" actions such as turning off lights, turning down thermostats in winter, turning off air-conditioners in summer, or driving more slowly. Instead we are referring to technological initatives such as changes in the construction of buildings and changes in equipment used in these buildings and in passenger travel.

We believe that several factors will motivate the pursuit of improved efficiency: increasing prices, uncertainty of reliable supply, possible Government incentives for conservation and disincentives against high energy consumption, and the availability of better technology. The price factor is very important. It is generally recognized that we are now entering a new era of higher energy prices. The notion that energy consumers will respond significantly by making substitutions in equipment and activities in the face of increased prices for energy seems obvious to us. However, the extent of the increases in energy prices, the time needed for consumers to become convinced of the changed conditions, the time required to retire old equipment, and the availability of suitable substitutes for inefficient equipment are all important factors in determining the pace of this response. Nonetheless, a significant response will eventually occur because increases in the cost of energy which are occurring will assume significant proportions in relation to the average consumer's budget.

B. Energy Prices and Their Role in the Economy

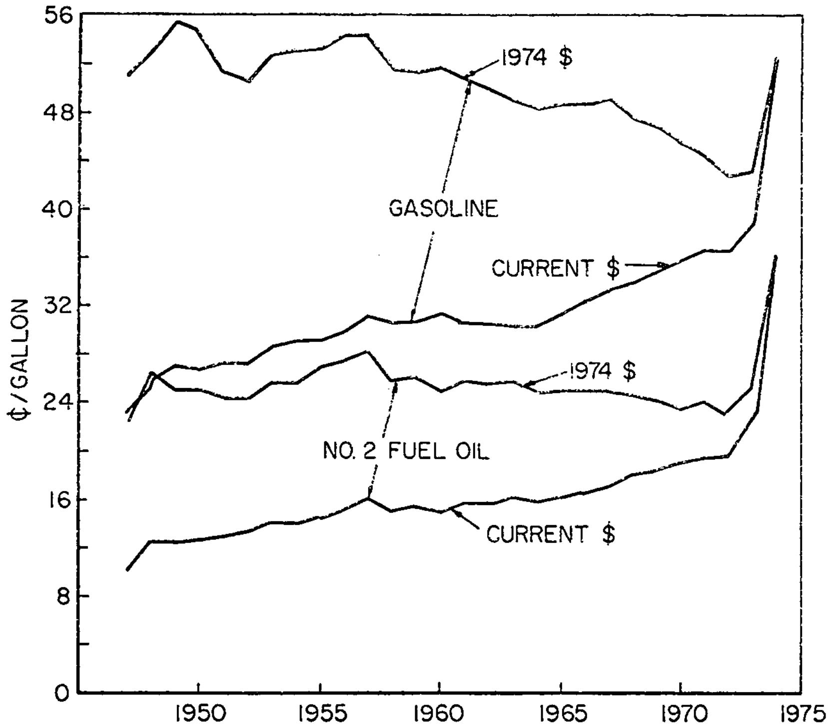
In the past fuel prices were remarkably low and stable, as shown in figures 3 and 4. Moreover, the real price of electricity (i.e., the price with effects of inflation removed) declined dramatically over time, decreasing between 1940 and 1970 at average rates of 5½ and 3½ percent per year in the residential and industrial sectors respectively. (See figure 5.)

FIGURE 3.—Wholesale fuel prices (1974 dollars). Fuel prices at the wellhead or minemouth were deflated by the wholesale price index for industrial commodities.



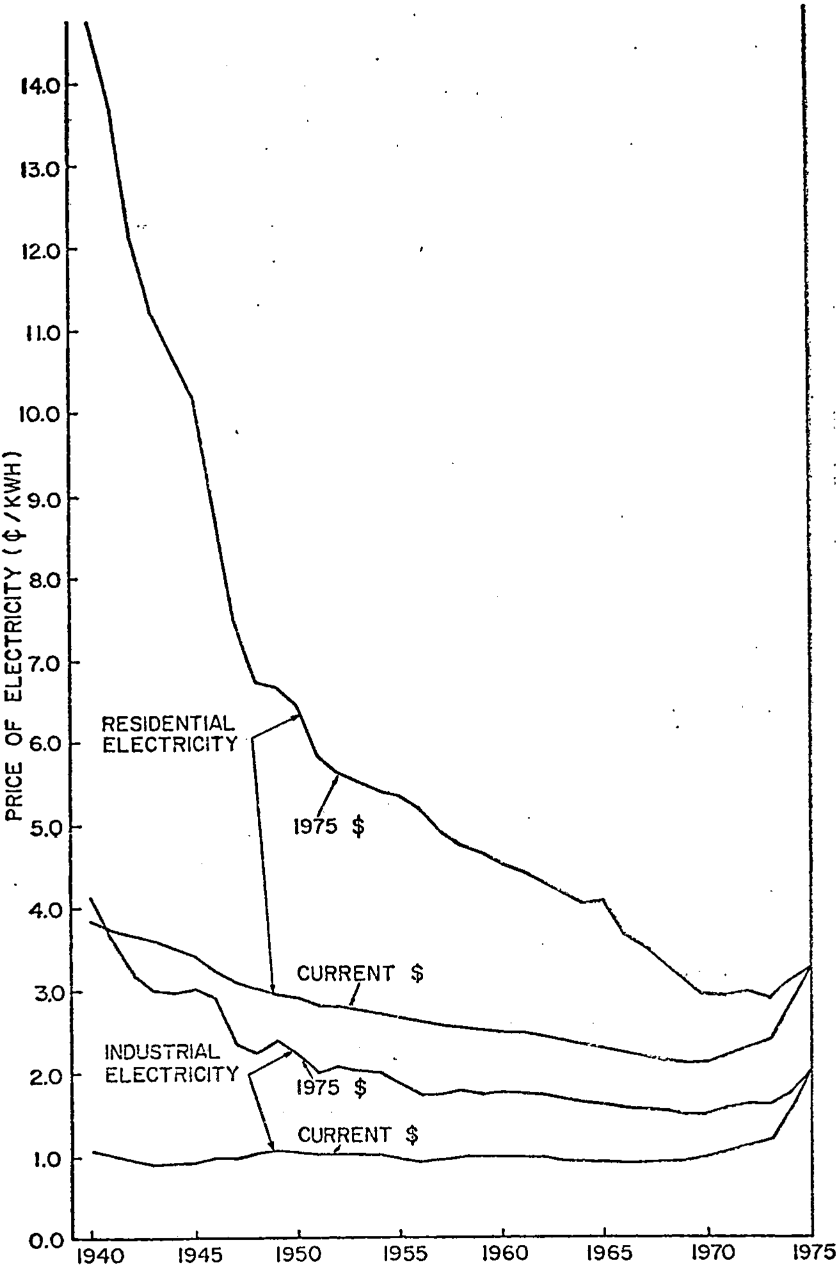
Sources: For oil and gas, American Petroleum Institute, "Basic Petroleum Data Book, Petroleum Industry Statistics," October 1975. For coal, The National Coal Association, "Coal Data," 1975 edition.

FIGURE 4.—Retail fuel prices (1974 dollars). Prices were deflated by the consumer price index.



Source: "Basic Petroleum Data Book."

FIGURE 5.—Electricity prices for residential and industrial customers in current and constant (1975) dollars. The price deflators were, for industrial electricity the wholesale price index for industrial products, and for residential electricity the consumer price index. Electricity prices in current dollars were obtained from the Edison Electric Institute.



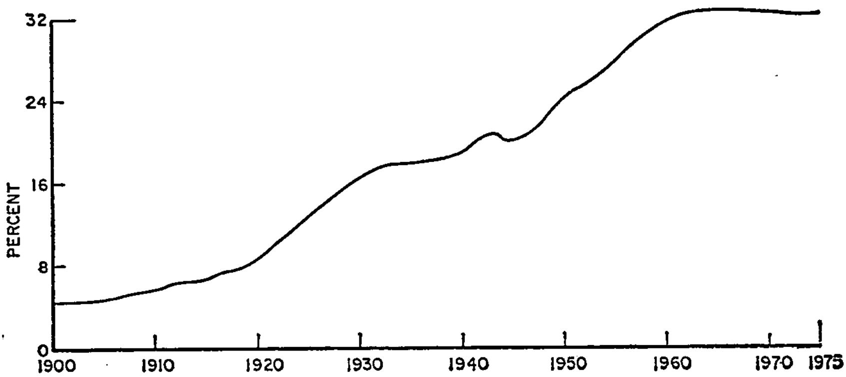
It is very likely that this era of stable low energy prices is over. While the sharp rise in fuel prices after 1973 was in response to price fixing by the OPEC cartel and thus does not directly reflect the marginal costs of new supplies, this dramatic political action was possible because the principal new energy resources of the world, except for OPEC oil, appear to be much more costly than energy resources have been historically.

The United States, like most other oil importing nations, is exploring opportunities for attaining energy self-sufficiency so as to become less vulnerable to actions like the October 1973 Arab oil embargo and cartel price fixing. But new oil and gas resources in the United States are going to be much more costly because they must be sought in environments that are more difficult to exploit, such as the Alaskan North Slope and the Outer Continental Shelves, while new oil reserves onshore from known reservoirs often will require the use of costly tertiary recovery technology. Gaseous and liquid synthetic fuels derived from coal and oil shale as substitutes for petroleum and natural gas will also require very costly new technology.

Coal and nuclear energy utilized as electricity are expected by Government and industry to provide for much of the overall growth in energy use, as the Nation continues the long-term trend toward an increasingly electrified economy. However, problems of high costs plague electric power generation as well. In part the recent reversal of the long-term downward price trend for electricity came about because of the hike in the world oil prices and its repercussions in markets for natural gas, coal, and uranium. However, close scrutiny of figure 5 shows that the price trend for electricity actually reversed before the oil embargo of 1973. Several factors underly this change. Concerns about air pollution are driving up the price of electricity based on coal, because of requirements to burn scarce and expensive low-sulfur coal or to install costly stack gas scrubbers. Quality control problems with nuclear powerplants and toughening regulations in response to public concerns about the hazards of nuclear energy have been driving up the cost of nuclear electricity as well.

In addition to such recent developments, however, there are factors of long-term significance underlying the recent price trend reversal for electricity. The rapid long-term decline in electricity prices reflected the cost reductions made possible through technological change and scale economies. One important measure of technological progress is the efficiency of converting fuel energy into electricity, shown in figure 6 for steam electric powerplants in the United States. Between 1900 and the early 1960's, a remarkable eightfold increase in efficiency was realized, before the average efficiency of steam electric powerplants leveled off at about 32 percent. While modest further increases in conversion efficiency are still possible, substantial further efficiency gains are unlikely, since present efficiencies for central station power generation are close to practical limits. (See section IV below.)

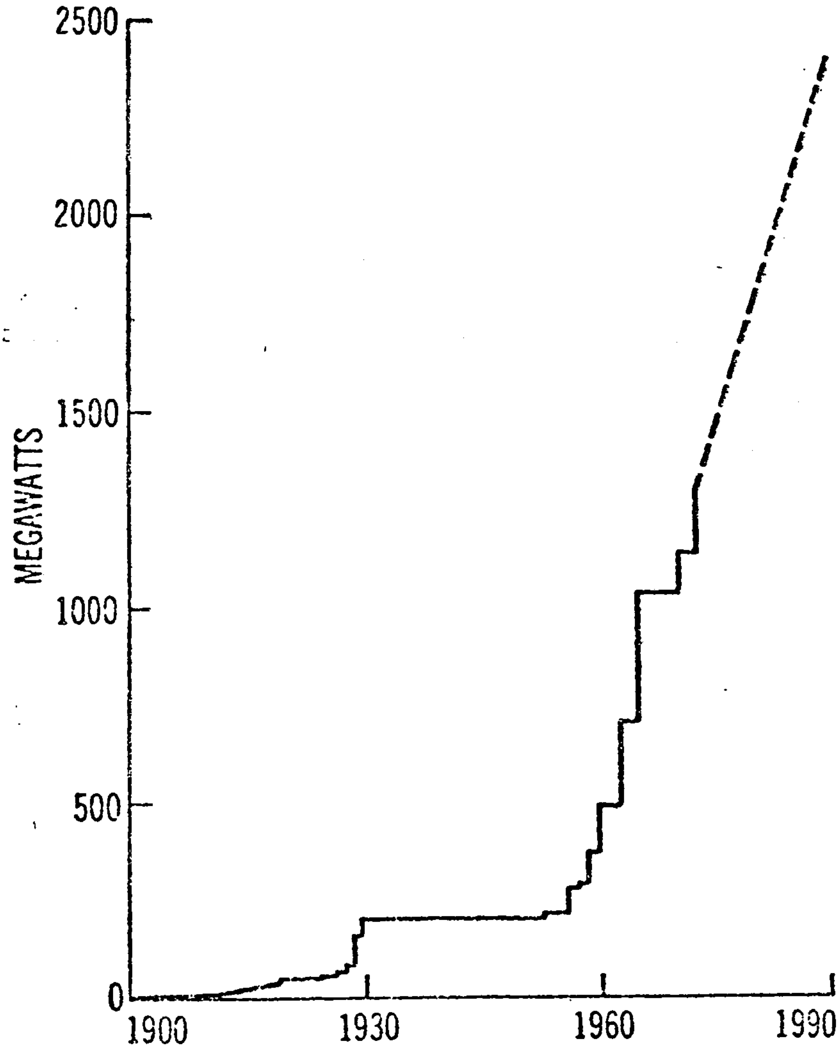
FIGURE 6.—Average steam electric power plant efficiency.



Sources: "Historical Statistics of the United States" and U.S. Bureau of Mines news releases.

As figure 5 shows, the price of electricity continued to drop rapidly even after efficiency improvements ceased in the early 1960's. This occurred in large part because of the strong emphasis given to cost cutting through scale economies in the 1960's. From 1930 till the early 1950's, the largest steam electric unit was about 200 megawatts. Then the swing to larger units began to be significant, with the largest unit in operation reaching 300 megawatts in 1955, 1,000 megawatts in 1968, and 1,150 megawatts in 1970. This trend is shown in figure 7, along with an extrapolation to the future made in the Federal Power Commission's "The 1970 National Power Survey".

FIGURE 7.—Largest fossil-fueled steam-electric turbine generators in service, 1900–1990.



Source: Federal Power Commission, "The 1970 National Power Survey," part I, December 1971.

While several years ago it was expected that continued cost cutting could be achieved with even larger units than the largest being built today, many analysts now feel that the point of diminishing returns in unit size may already have been reached or exceeded and that this has been an important factor in the enormous rise in capital costs over recent years. This more pessimistic view that cost-cutting opportunities in central-station power generation are exhausted is reflected in projections of future electricity prices. The industry journal "Electrical World" [11] now projects that the price of residential electricity will increase at an average rate of about 2 percent per year faster than general inflation through 1985, and ERDA's Institute for Energy Analysis has projected [12] this same rate of inflation for the overall price of electricity through the year 2000. We feel that the IEA electricity price projection is probably fairly realistic (if not an underestimate) because it is what would happen if the average price of electricity rose by the year 2000 to the marginal cost for power from new plants ordered today. [13] While 2 percent real inflation seems fairly modest in absolute terms, this rate of price increase is a dramatic shift from the 3- to 5-percent-per-year historical rates of decline in electricity prices.

In the last several years, economists have been developing models based on historical data to predict how energy consumption and the mix of fuel forms might change in response to higher prices. There is no consensus emerging as to what the correct price elasticities of demand are, however, showing the tremendous difficulties involved in isolating significant price/consumption relationships in the historical data. Also these studies are based largely on data from the era of declining prices, which may not be especially relevant for the new era of rising prices.

Despite these problems, it is worth describing briefly how rising energy prices might affect economic activity. A given level of economic product requires inputs of capital, labor, materials, and energy. To a certain extent, these inputs are substitutable, so that less of one and more of others can yield the same output. The mix of inputs chosen depends on both the relative prices of the inputs and Government policies that influence market decisions, through either regulations or tax incentives and disincentives. Rising prices and new nonmarket influences (regulatory constraints on certain energy forms, incentives for fuel conservation, etc.) are factors that have not affected U.S. energy demand significantly in the past but are likely to be important from now on.

It is useful to examine the historical record to see how various factors contribute to economic product. Consider manufacturing. Table 1 shows substantial changes in prices and quantities of capital, labor, energy, and materials used in manufacturing during the period 1947–71. Table 2 shows, however, that the share of total cost associated with each of the manufacturing inputs—capital, labor, energy, and materials—remained remarkably stable during this period, even though the rates of price increases for these inputs varied widely. The relatively stable prices for capital and energy resulted in much more rapid growth for these inputs than for labor. As pointed out by Berndt and Wood, [8] the very low average increase in the price of capital in part reflects favorable Government policies toward corporations investing in new plant and equipment (the accelerated depreciation allowance and investment tax credits) Similarly, the relatively slow rise in the price of energy reflects in part Government price ceilings on certain energy forms (primarily the regulation of natural gas prices).

TABLE 1.—AVERAGE ANNUAL GROWTH RATES FOR PRICES AND QUANTITIES OF CAPITAL, LABOR, ENERGY, AND OTHER MATERIAL INPUTS TO MANUFACTURING, 1947-71

	Price [1]	Quantity
Capital	0.8	4.3
Labor	4.3	1.8
Energy	2.1	3.5
Materials	1.8	3.3

[1] These growth rates are for prices expressed in current, not constant dollars. The wholesale price index for all industrial commodities grew at an average rate of 2 percent per year in this period.

Source: Reference 8.

TABLE 2.—COST SHARES FOR CAPITAL, LABOR, ENERGY, AND OTHER INTERMEDIATE MATERIALS—U.S. MANUFACTURING, 1947-71

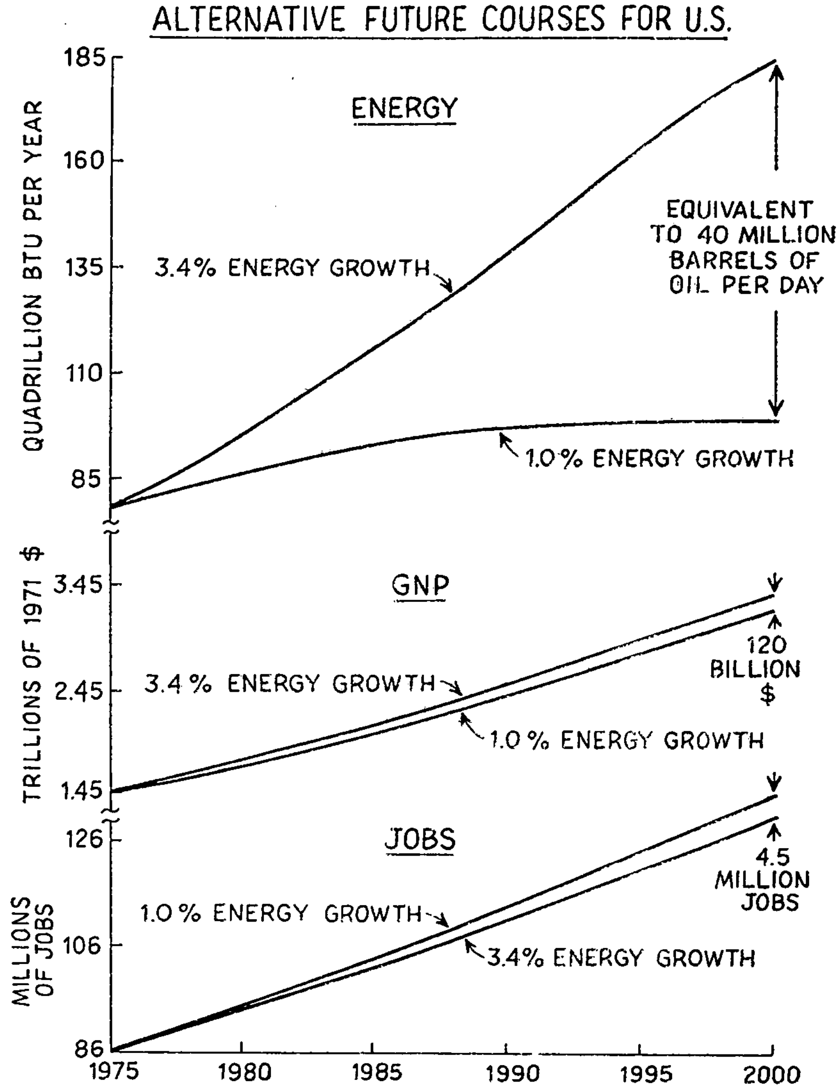
	Capital	Labor	Energy	Materials
1947	0.051	0.247	0.043	0.659
1948	.058	.277	.051	.613
1949	.046	.259	.051	.644
1950	.050	.248	.046	.656
1951	.050	.255	.045	.650
1952	.049	.267	.045	.640
1953	.047	.268	.044	.641
1954	.056	.272	.048	.624
1955	.053	.265	.045	.638
1956	.046	.269	.046	.639
1957	.050	.272	.048	.630
1958	.060	.273	.048	.619
1959	.062	.273	.046	.619
1960	.058	.277	.046	.619
1961	.059	.278	.046	.616
1962	.056	.283	.045	.616
1963	.056	.280	.045	.620
1964	.055	.283	.044	.618
1965	.055	.280	.041	.624
1966	.055	.284	.040	.622
1967	.054	.286	.041	.618
1968	.058	.289	.040	.614
1969	.054	.290	.040	.616
1970	.053	.298	.043	.606
1971	.047	.289	.045	.619

Source: Reference 8.

If, in the future, energy prices rise more rapidly than the prices of other inputs, we should expect a different mix of inputs to evolve for manufacturing. On the basis of a review of historical experience concerning the roles of various inputs to manufacturing, Berndt and Wood found that demand for energy by manufacturers would be responsive to price, with an elasticity of about −0.5; that is, a 1-percent increase in price would result in a one-half percent reduction in demand. Would this energy demand reduction seriously curtail output capacity? According to Berndt and Wood, there are opportunities for substituting other inputs for energy. They found that, to some extent, labor and energy are substitutable inputs. Substitutability of capital for energy is slightly more complex. The discussions in section IV show that new capital investment in a given energy-intensive activity can, in most instances, be used to improve energy performance. But aggregate historical data suggest that low-cost capital stimulates the demand for energy by encouraging activities that are both capital- and energy-intensive.

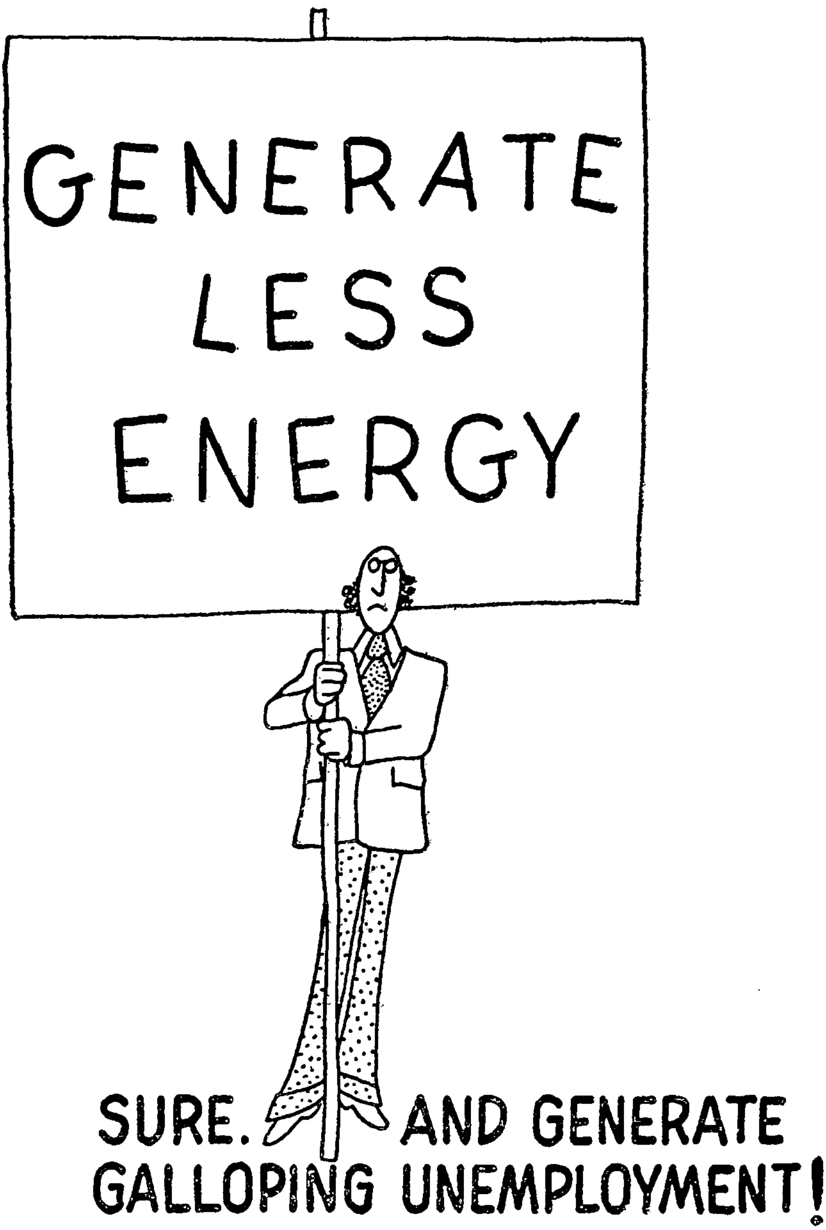
An analysis similar to that of Berndt and Wood has been carried out by Hudson and Jorgenson for the economy as a whole. [14] Hudson and Jorgenson also found that there are significant opportunities to substitute other inputs for energy throughout the economy. However, they point out that in sectors other than manufacturing, energy and capital tend to be substitutable, reflecting widespread opportunities for fuel conservation through installation of more energy efficient equipment. Hudson and Jorgenson have developed an econometric model for studying alternative courses for economic and energy growth in the United States. In one application of this model they constructed alternative energy futures for the Ford Foundation's Energy Policy Project. [14] The two alternative futures to the year 2000, shown in figure 8, reflect different energy prices. For the course involving 1 percent average annual energy growth, an energy tax is imposed gradually between now and the year 2000, when it amounts to about 15 percent of the average price of energy. In addition to the Btu tax, however, pessimistic assumptions are made about the untaxed price of energy in this low energy growth case. For example, while the high energy growth track involves a decline in the real price of electricity of 2.7 percent per year (a return to the historical conditions for the period 1965–72), an assumption underlying the low growth projection is that the real price of electricity will grow faster than general inflation by 1.7 percent per year. (As we have pointed out above this latter assumption is more realistic. In fact the real price of electricity may grow even more rapidly.) The substitution effect in moving to the lower growth path, according to the Hudson-Jorgenson model, would be a small increment in employment (perhaps amounting to 4.5 million extra jobs by 2000), but an enormous reduction in energy use. There would be a slight penalty in terms of GNP, but this would amount to only a loss of about 1 year's growth out of 25 between 1975 and 2000.

FIGURE 8.—Examples of alternative future courses for the United States. The development of the economy is projected by an econometric model assuming two different price paths for energy. See text. Data taken from reference 14.



These calculations suggest that energy growth could be sharply curtailed in response to rising energy prices without adversely affecting the economy, because there are considerable opportunities for substituting other inputs for energy throughout the economy. These results, of course, are contrary to the "conventional widsom," depicted in figure 9. The viewpoint illustrated by the figure would be correct if the Nation, while planning to continue historical energy growth, were suddenly confronted with cutbacks in energy supply. With a physical plant structure geared to a high level of energy inputs, there would undoubtedly be plant shutdowns and widespread unemployment in response to unexpected shortfalls in energy supply. The analysis presented here refers to a vastly different situation in which Government, corporations, and individuals throughout the economy develop less energy dependent substitutes for present practices. With new investment and energy tax policies, this transition to reduced energy growth could be achieved with minimal dislocations.

FIGURE 9.—The conventional wisdom.



91-592—77——4

A problem concerning the potential for substituting labor for energy has been raised by Hannon, [15] who has studied in detail the energy and labor intensities of goods and services throughout the economy. He points out that shifting from energy-intensive to labor-intensive products or processes will often involve shifting from highly specialized, strongly unionized work to less specialized weakly unionized work with the result that society may resist labor-for-energy substitutions.

Another problem with analyses like that of Hudson and Jorgenson [14] is that they are based on the use of econometric models, the validity of which for long-term forecasting is not well established. One should not be persuaded by these analyses alone, therefore, that energy and economic growth can be substantially "decoupled." But while the precise response of consumers to higher energy prices cannot be predicted with confidence at this time, it is clear that unless consumers make substantial adjustments to higher energy prices there will be substantial changes in consumer spending patterns. This statement arises from the observation that for various classes of energy consumers the fraction of total expenditures committed for energy purchases has been fairly constant over time, as shown in figure 10. Note especially that, during the period 1950 to 1970, the percentage of GNP spent on electricity remained close to 2 percent, despite the fact that in this period real GNP grew at 3½ percent per year, electricity consumption grew at 8 percent per year, and the real price of electricity fell nearly 3½ percent per year. Unless future consumer demand for electricity is substantially moderated as a response to higher prices, the historical stability of consumer expenditures for electricity will be disrupted. Utility industry forecasts for future electricity demand are now lower than they were a couple years ago. However, current industry projections still have electricity use growing rapidly, at about 5 percent per year. This growth, along with the price of electricity growing 2 percent per year faster than general inflation would result in the fraction of GNP spent on electricity rising to more than 8 percent by 2000 [1]—or more than 4 times the "historical" share. (Electricity use would have to grow no faster than 1 to 2 percent per year to maintain the "historical trend" shown in figure 10.) This greater share of expenditures for electricity would have to be offset by lesser shares for other goods and services. Similar observations can be made about industrial expenditures for energy as a fraction of total manufacturing costs and about consumer expenditures for energy as a fraction of total personal consumption expenditures. (As shown in figure 10 both of these quantities were stable in the past.) This dampening effect of higher energy prices on nonenergy economic activity provides a strong motivation for seeking opportunities to use energy more efficiently.

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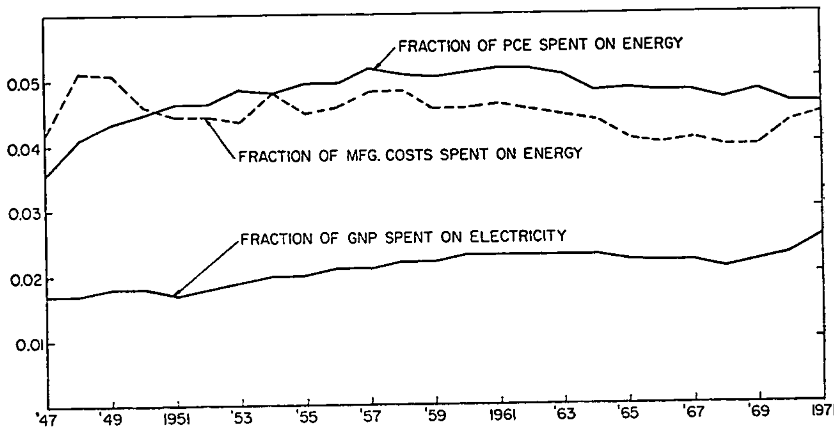
[1] For an average GNP growth rate of 3.2 percent per year. See sec. II.D.

FIGURE 10.—The fraction of personal consumption expenditures (PCE) and manufacturing (MFG) costs spent on energy and the fraction of GNP spent on electricity. The curve for PCE involves producers' prices and is based on data in H. S. Houthakker and D. W. Jorgenson, "Energy Resources and Economic Growth," draft final report to the Ford Foundation's Energy Policy Project (unpublished). The curve for the share of manufacturing costs spent on energy is based on data in reference 8. The electricity sales data were obtained for 1959 to the present from "Statistical Yearbook of the Electric Utility Industry," published by the Edison Electric Institute, and for 1947–58 from the Institute's "Historical Statistics of the Electric Utility Industry."



C. ENERGY AND THE EVOLVING MIX OF FINAL PRODUCTS

As pointed out above, the economy has experienced a greater growth in services than in goods production, and in goods production there has been less emphasis on basic materials production and more on the fabricating industries. This continuing trend could help to ease the pressures of higher energy prices. To understand the energy implications of these trends it is useful to examine the energy consumption associated with purchases by final consumers.

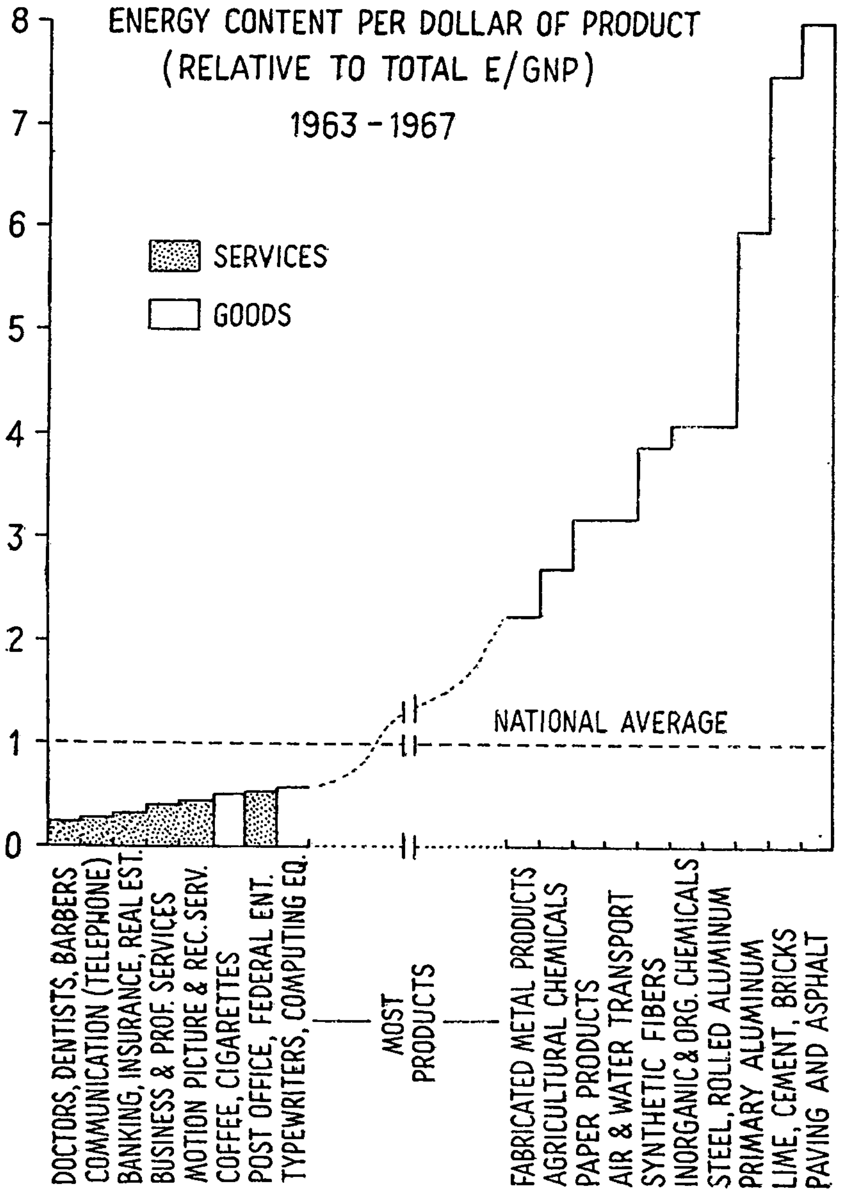
About one-third of all U.S. energy consumption is purchased directly for personal consumption (mainly for residential and automobile uses). The other two-thirds is consumed by producers in the process of providing goods and services for final purchasers. In this section we emphasize this latter category of energy use.

1. *Specific Energies of Products*

In figure 11 we show the fuel use associated with the purchase of a dollar's worth of various types of products.[2] Such energy-per-dollar numbers have been calculated by Herendeen and Bullard for 357 industrial classifications covering the U.S. economy in 1963 and 1967. [16] Reardon has provided a similar analysis for fewer sectors for 1947, 1958, and 1963. [17] These specific energies include the fuel consumption by the supplier of the product, the fuel consumption by the supplier's suppliers, and so on. In other words, each specific energy comprises all the energy required directly and indirectly to provide a dollar's worth of product to a consumer.[3]

[2] Primary fuel consumption is considered throughout this paper, unless otherwise stated. Electrical energy is quoted in terms of primary fuel consumed to generate it (usually according to Bureau of Mines accounting).
[3] The computation of specific energies is done via input-output analysis.

FIGURE 11.—Total energy consumption associated with each dollar of product purchased (1963–67 average), for various product categories. The data were obtained from reference 16.



The national average specific energy, that is, the total fuel consumption divided by gross national product (E/GNP) was 63,000 Btu/dollar in 1967. Of the 357 classifications, about 20 percent had specific energies which were either more than twice this average or less than half of it. As shown in figure 11 the highest energy use classification was asphalt paving, with cement, primary aluminum, steel and chemicals close behind. All of these are basic materials processing industries that require much energy, material and capital but relatively little labor.[4] At the low end of the scale, about one-quarter to one-half the national average, are services such as insurance, real estate, banking, barber and beauty shops, medical and dental care, and communication services (telephone); electric and electronic equipment (such as typewriters, sewing machines, radio and TV equipment, and computing equipment); and special nondurable items such as coffee and cigarettes. At one extreme, in the purchase of materials such as asphalt, cement or unfabricated aluminum, about as much energy would be involved per dollar as is obtained in the purchase of gasoline at the filling station. At the other extreme, in getting a haircut or purchasing medical services, only one-twentyfifth as much energy is involved per dollar as when one spends the same amount of money on gasoline. Most goods purchased by consumers, however, tend to be clustered near the national average energy-GNP ratio, as shown in figure 11.

Classifying consumer purchases into goods and services tends to separate high from low energy-per-dollar products. We group among services primarily personal service products such as health, education, recreation, and repair, as well as finance and business services and communications. There is considerable arbitrariness in defining services as distinct from goods. [18] In order to make the distinction more useful for energy analysis, we have identified the most energy intensive products which are sometimes defined as services and grouped them with the goods. Specifically we do not include electric, gas or water utilities or public transport among services, although the the U.S. Department of Commerce does so.

Figure 11 shows that the important service categories have low specific energy, that is, low energy consumption per dollar. Figure 12 shows that the average specific energy for services is about one-third of that for goods. It is perhaps useful to repeat that these energy consumption per dollar figures are categorized according to products as finally consumed. Thus the energy use associated with hair cuts includes not only the barber's direct energy consumption but also the energy required to provide all the equipment of his trade, for example, the energy consumed to provide the scissors.

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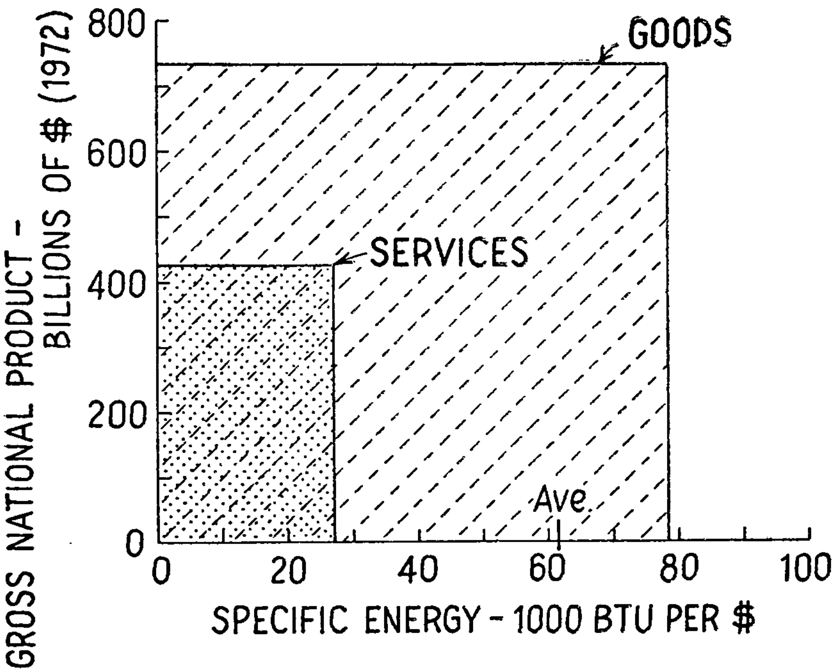
[4] These very high specific energy products are shown here for general information. It should be noted that they are not products usually bought by final consumers.

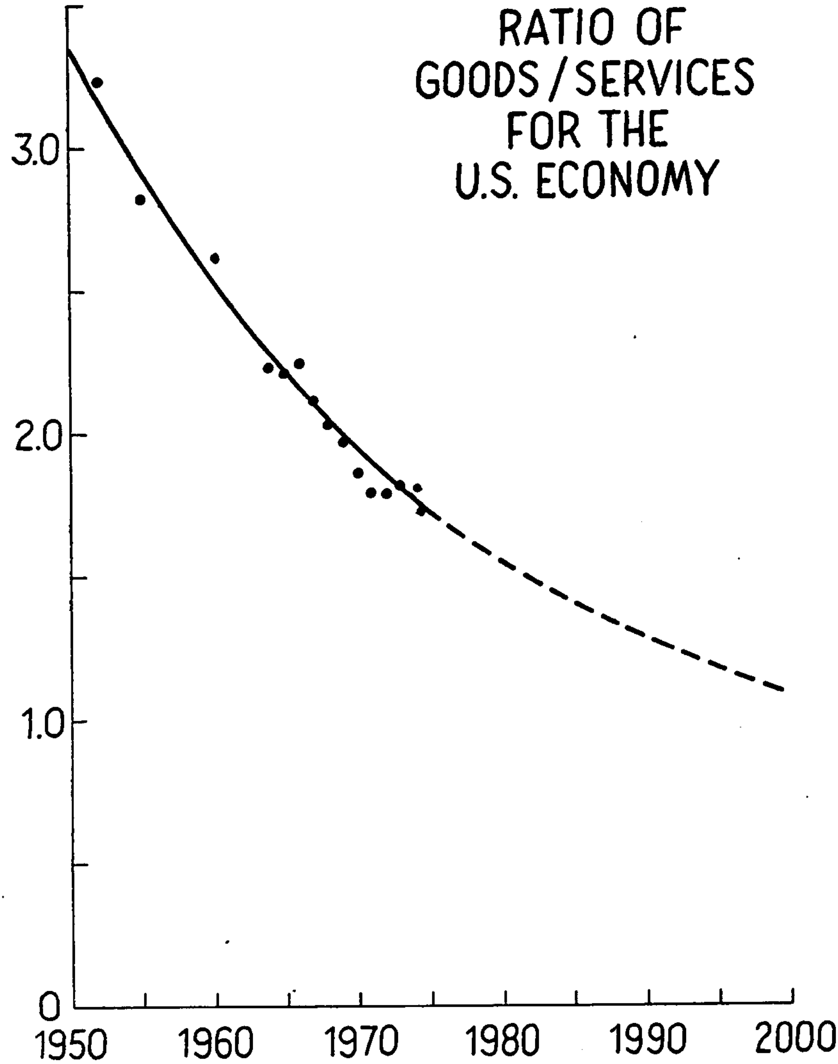
FIGURE 12.—Final demand versus specific energy for goods and services in 1972. The area of the rectangle shown for each sector is equal to the total energy consumed to provide goods or services to final demand. The sum of these rectangular areas is equal to total U.S. energy consumption. Energy and sanitary utilities and public transport are included in the goods sector. All items not classified as services in the gross national product are counted as goods. Determined from data taken from reference 16, Survey of Current Business, July 1974, and "The Input-Output Structure of the U.S. Economy: 1967", Survey of Current Business, February 1974.



2. The Shift to Services

Because service products are less energy-intensive than goods, the growing trend away from goods and toward services in the economy (see figure 13) has contributed to the gradual decline in the energy-GNP ratio for the U.S. economy shown in figure 2. The reduction in this ratio for the period 1947–67 can be largely attributed to this shift to services, to the efficiency improvements in basic materials processing industries, and to the shift in manufacturing from basic materials to fabrication.

FIGURE 13.—The ratio of the value of goods to the value of services to final demand in current dollars in the U.S. economy. The classification and accounting methods are not exactly the same as for figure 12. Differing rates of inflation for goods and services accounted for about 30 percent of the change in the 24-year period shown. The crude extrapolation shown is for an exercise discussed in the text. Data from various issues of Survey of Current Business.



A continuation of this trend toward a "post-industrial economy" can be expected to lead to a further gradual reduction in the energy-GNP ratio. If the trend in the ratio of goods to services in the economy should persist as extrapolated in figure 13 and if the specific energies should not change from what they are in figure 12, then the energy-GNP ratio would decline by about 10 percent over 25 years from the 1973 level of about 58,000 Btu per (1973) dollar. Since this calculation includes both direct and indirect energy inputs into final goods and services, it takes into account the goods production needed to provide services and the services needed to produce goods. However, the calculation is simplified in two respects: (1) It is based on fixed technology, and (2) it ignores the fact that there will be a continuing change in the product mix within both the goods and the service sectors that will cause additional changes in the energy-GNP ratio even with fixed technology.

The possibility for shifts in energy per dollar within a given sector is substantial and could lead either to a lower or to a higher average specific energy for a sector. For example, especially rapid growth in electronics products implies, other things being equal, a reduction in energy per dollar of goods purchased, because the manufacture of electronic devices is not energy intensive. (Even the energy consumption by the consumer in operating electronic devices is usually low.) Also the aggregate calculation we have made here will underestimate the effects of rising energy prices and fuel conserving policies on the mix of technologies and products.

On the other hand, consumers actually engage in "activities" involving a combination of products. Some services, in particular, tend to be associated with considerable consumer travel. For example, amusement as a consumer activity has an energy per dollar coefficient nearer the national average E/GNP than does the amusement services category as a product, because growth in amusement services tends to be associated with growth in the use of gasoline. Thus we have underestimated the energy consumption associated with the growth of some services.

Despite these uncertainties we believe that the net effect of a changing product mix in the economy over the next decade or two will be to reduce the energy use per dollar of product. However, we feel that the reduction in energy use that will be achieved this way will be small compared to the reduction in energy use that could be realized through the pursuit of the fuel conservation measures described in section IV.

D. Energy Implications of Emerging GNP Growth Trends

Most major energy projections advanced by government and industry are based on the assumption of continued rapid growth in GNP. For example, the forecasts in both the 1972 National Petroleum Council study [19] and a Department of Interior study [20] envision GNP growth till 1985 at about 4.2 percent per year, the average growth rate for the period 1963–73. Careful examination of the factors driving the economy, however, suggests a gradual but continual slowdown in future GNP growth.

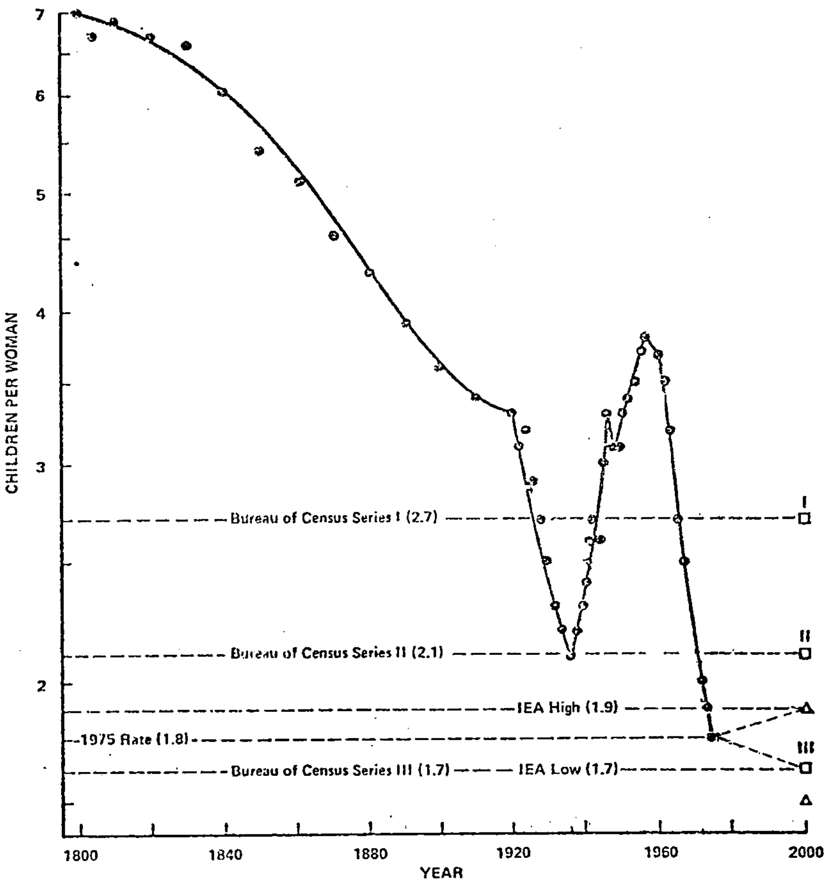
Recently ERDA's Institute for Energy Analysis (IEA) examined these emerging GNP growth trends in a study on energy and economic growth. [12] The IEA study concluded that even with optimistic expectations about labor productivity in the future, GNP growth is likely to slow down continually over many years for demographic reasons.

In the IEA study GNP is expressed as a product of two factors, employment [5] and labor productivity. It analyzes historical trends and makes projections for both factors. The IEA authors point out that the exceptionally vigorous GNP growth in the period 1963–73 was in large part due to the very large increase in employment, which grew at an average rate of about 2.5 percent per year in this period, compared to 1.4 percent per year for the post war period, 1947–63. The large growth in employment for the period 1963–73 is a consequence of the World War II baby boom, which interrupted a long term downward trend in U.S. fertility rates, as shown in figure 14. The mature population is still growing fairly rapidly because of the "tail end" of the baby boom, but this growth will have run its course in the very near future. Established trends indicate that fertility rates will continue to decline or will stabilize in the future. IEA considers two cases where the recent sharp downward trend stabilizes—a low case, in which fertility declines slightly by 2000 from the 1975 level of 1.8 children per woman (the U.S. Bureau of Census Series III projection), and a high case which involves a slight increase from the present fertility level. The fertility rate in a given year gives rise to a change in the labor force some 16 or more years later. The IEA study points out that even if the fraction of those of working age who participate in the labor force increases from the present level (arising mainly as the net effect of two contrary trends: the continued increase in the number of women in the labor force and the increasing percentage of retirees in the population), we can expect a dramatic decline in the growth rate of the labor force over time. During the 1960's and early 1970's the labor force grew at an average rate of 1.7 percent per year. From 1975 to 1980 a modest increase can be expected, but the IEA study projects that the growth rate should decrease dramatically thereafter to 1.2 percent per year for 1980–85; 1.0 percent per year for 1985–90; and 0.6–0.7 percent per year for 1990–2000.

[5] Defined as the number of full-time-equivalent jobs.

91-592—77——5

FIGURE 14.—U.S. fertility rates. Historical data and projections to the year 2000.



Source: Reference 12.

In making its GNP projections IEA assumes that employment grows faster than the labor force out to 1985 [6] and thereafter at the same rate as the labor force. For productivity growth the IEA projected a rate of 1.7 percent per year out to 1985, followed by an increase to 2.0–2.2 percent per year for 1985–2000. Combining these factors gives rise to a GNP growth rate of 3.6 percent per year for 1975–85 and 2.7–3.0 percent per year for 1985–2000.

While these GNP projections are lower than most earlier industry and Government forecasts, they should be regarded as optimistic. They assume both the success of policies aimed at restoring and sustaining full employment and that productivity will grow rapidly in the future. As the IEA authors point out, "We have tried to bias our results on the high side. For example, we have used optimistic assumptions

[6] It is assumed that in the decade, 1975–85, the United States returns to a "full employment" economy (i.e., 4 to 5 percent unemployment), so that employment growth would average 1.9 percent per year in this period.

about future labor productivity . . . ." In the IEA report many reasons are given why one might expect future productivity growth rates to be lower than in the past: The continuing trend of ever slower growth in the "quality" of the U.S. labor force, increased investment requirements not related to production (that is, related to environmental protection and occupational and public health and safety), a growing share of investment going into replacement outlays, as opposed to new investment, and a continuing decline in the relative importance of agriculture—historically the sector of the economy with the most rapidly increasing productivity. Despite these factors the IEA authors optimistically assume that the productivity growth rate for the next quarter century will be faster than the 1.7 percent annual average for the last 25 years and that there will be a dramatic comeback from the 1.1 percent average for the period 1965–75. Indeed the IEA productivity growth projections fall at the high end of the range (1.5 to 2.25 percent per year) assumed for future productivity growth in a 1972 report of the U.S. Commission on Population Growth and the American Future. [21].

Nevertheless if we assume the IEA rates for growth of GNP and a continuation of the historical slight downward trend in the E/GNP ratio shown in figure 2 (0.6 percent per year for the period 1947–75), energy would grow no faster than about 3 percent per year in the period 1975–85, and 2.3 percent per year for 1985–2000. The result would be energy consumption amounting to 132 quads[7] in 2000, compared to 192 quads projected in the 1972 U.S. Department of Interior study cited above [20] and 162 quads in an updated 1975 projection. [22] This slower growth does not reflect the potential for accelerating the decline in the E/GNP ratio through higher prices or Government initiatives to spur energy conservation efforts. Thus this projection corresponds to a "business as usual" energy future. The fact that it would give rise to a rate of energy consumption in the year 2000 which is not much greater than what has been projected by some analysts to result from the pursuit of aggressive energy conservation efforts [23,24] simply shows that these "conservation projections" are based on unrealistically high GNP growth rates.

[7] One quad equals one quadrillion (10^{15}) Btu.

III. INTERNATIONAL COMPARISONS OF ENERGY CONSUMPTION [1]

Future growth in energy consumption will likely be considerably slower than in the "business as usual" energy projection described above because of sharply increased energy prices and new policies to encourage fuel conservation. Foreign experience is suggestive of the opportunities for fuel savings. Here we summarize results of studies of energy use in Sweden by Schipper and Lichtenberg [26] and in Germany by Goen and White. [27] The fact the per capita gross national product is similar in these countries and the United States, and that the proportion of heavy industry is similar suggests that comparisons may be useful. Nevertheless conditions differ in these countries, and energy accounts and gross product levels [28] are hard to calibrate accurately, so that comparisons must be made with some care.

In figure 15, per capita energy use is plotted with respect to per capita GDP for West Germany and the United States. Also the change in recent years prior to the 1973 oil embargo is shown. It is seen that not only is the E/GDP ratio smaller in West Germany, but also the increase in energy consumption associated with an increase in GDP has been smaller on the average in recent years.

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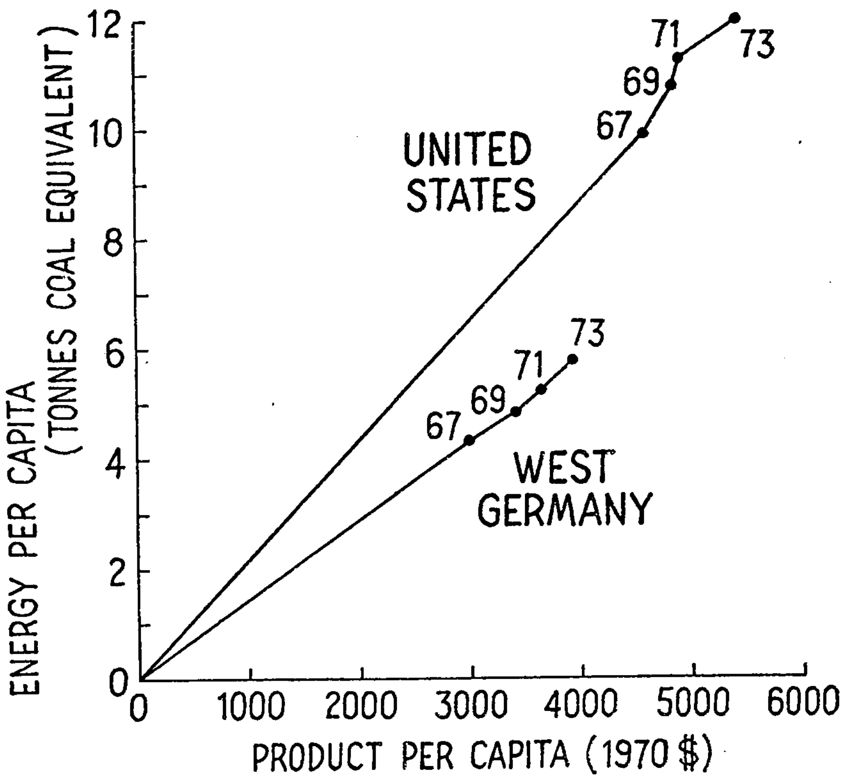
[1] A study (reference 25) made available to the authors after the present study was completed makes comparisons of energy use and economic activity in nine high income countries. The conclusions of that study in general support the conclusions arrived at in the much more limited review presented here.

FIGURE 15.—Per capita energy consumption and gross domestic product of the United States and West Germany for 1967, 1969, 1971, and 1973. Careful examination of the figure shows that both the E/GDP ratio and its rate of change are substantially smaller for Germany than for the United States. Thus, substantially less energy—about two-thirds as much—is associated with each dollar of product in Germany compared with the United States, and there was no tendency for the energy per dollar of product in Germany to change over the period 1969–73. It is especially noteworthy that the high level of affluence achieved by Germany during that period was not associated with an increase in energy consumption per dollar of product. The GDP numbers are expressed in 1970 dollars. The GDP's in constant units of domestic currency were taken from "National Accounts of OECD Countries"; the comparison of GDP's was then made for 1970 using reference 28, which compares purchasing power within each nation rather than using exchange rates. The energy data are from the "U.N. Statistical Yearbook."



Summary information on per capita gross national product and energy use by economic sector for these countries is presented in table 3. For each sector, we shall discuss the international differences in per capita energy use, showing by examples how energy consumption varies with the type of equipment used in the different nations, and how it depends on the detailed nature and mix of the products consumed.

TABLE 3.—SWEDISH AND GERMAN PER CAPITA INDICATORS RELATIVE TO THE UNITED STATES [1]

[In percent of U.S. levels]

	Sweden,[2] 1971	West Germany,[3] 1972
Gross national product per capita [4]	88	70
Energy use per cpaita:		
Residential/commercial	76	52
Industrial [5]	75	61
Transportation	32	26
Total energy	65	49
Net energy [6]	59	46
Energy per gross national product [7]	67	66

[1] In this table and the following 2 tables, electricity has been counted at approximately 3 times the electrical energy; i.e., in terms of equivalent primary fuel energy, even for hydroelectricity.
[2] Schipper and Lichtenberg, reference 26.
[3] Goen and White, reference 27.
[4] Based on exchange rates. For Germany a comparison based on actual purchasing power shows that in 1970 the GNP per capita in West Germany was 75 percent of that in the United States. See I. B. Kravis et al., reference 28. A draft study (reference 25) made available to the authors after the present study was completed estimates Swedish per capita gross domestic production the basis of actual purchasing power and shows that in the case of Sweden the effect would be to decrease very slightly the per capita GNP for 1972 from that estimated on the basis of the exchange rate.
[5] Includes use of fuel as feedstock, and, for Sweden, noncommercial fuels.
[6] Total energy corrected for export/import energy content of goods.
[7] Net energy per GNP.

A. Residential-Commercial Energy Use

The use of energy in buildings in these countries is summarized in table 4. In Sweden, the climate is much more severe but per capita energy use for residential heating is somewhat less than in the United States. In Germany, the climate is somewhat more severe and per capita energy use for residential heating is two-thirds that of the United States. In order to interpret this information it is important, to consider the role of climate and floor space.

TABLE 4.—PER CAPITA RESIDENTIAL ENERGY USE RELATIVE TO THE UNITED STATES

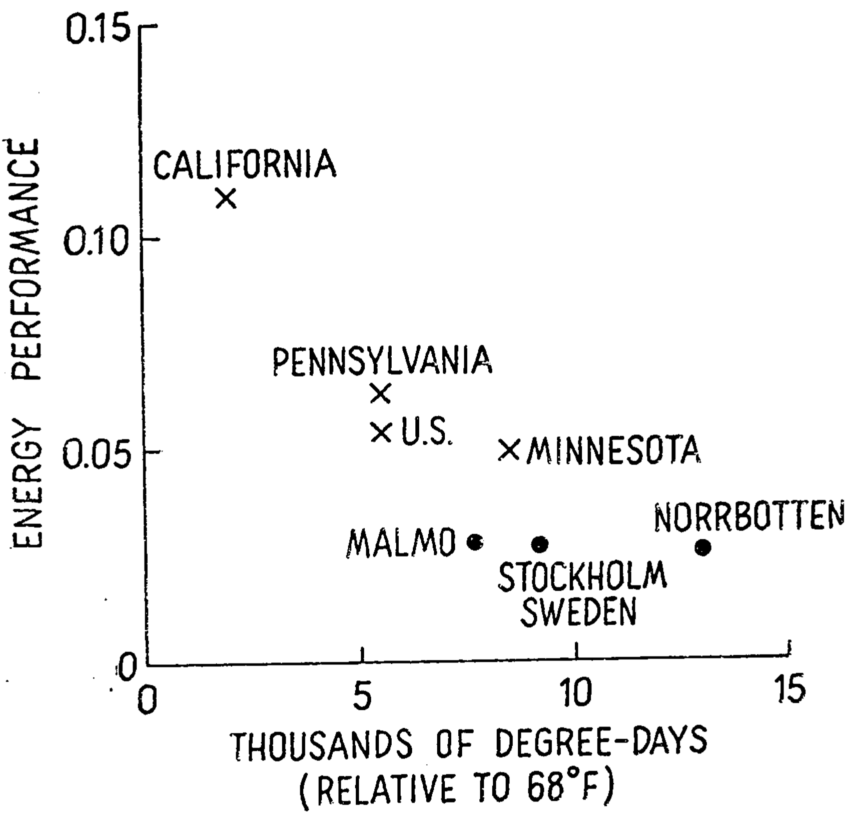
[In percent of U.S. levels]

	Sweden,[1] 1972	West Germany,[2] 1972
Space heating	74	67
Heating energy without taking into account district heat savings	(87)	--
Water heating	105	37
Air-conditioning	Nil	Nil
Clothes drying	Nil	Nil
Refrigeration and cooking	70	--
Lighting	31	28
Total	76	48

[1] Reference 26.
[2] Reference 27.

In Sweden the floor area per capita is similar to that in the United States but the energy use for heating, corrected for both climate and floor space differences, is roughly half that of the United States, reflecting better construction. The better construction reflects, in turn, tough regulations coupled with a centralized building industry. This Swedish achievement is illustrated in figure 16 where building performance is shown for different climatic conditions. The figures show that the quality of construction improves with severity of climate in the United States, but that Swedish results are substantially better than would be expected from U.S. experience. It is noteworthy that Sweden has recently revised its building codes with the objective of reducing heating fuel requirements in new buildings by another 40 percent. [29]

FIGURE 16.—The heating performance of typical fossil-fuel heated housing in the United States and Sweden versus severity of climate in degree days. Performance is measured in thermal kilowatt hours per square meter of floor space area per degree day.



Source: Reference 26 and the American Gas Association.

A further, though less important, reason for the lower overall fuel consumption for residential, and commercial, space heating in Sweden is the use of "district heating," where a centralized boiler generating steam provides heat for several buildings or for a whole area of a city. About one-third of these centralized heating systems involve the cogeneration of electricity and hot water or steam near the point of heat use. As much as one-third of the fuel can be saved in such cogeneration systems compared to separate generation of heat and electricity. In Sweden the overall net savings associated with district heating systems is 14 percent of the heating energy, equivalent to 2 percent of total national energy consumption.

In Germany, lower per capita floor area, the custom of allowing some rooms to drift to low temperature,[2] and lower interior temperatures generally appear to be the major factors in the reduced use of fuel for heating compared with the United States. Differences in con-

[2] Maintaining different temperatures in different areas of a building, or zonal heating, is a common practice in Europe.

struction standards are less important. In both Sweden and Germany multiple family dwellings are more prevalent than in the United States. One would expect that multiple family dwellings would require less heating fuel per unit of floor space than single family dwellings,[3] but, because of poor control equipment and perhaps because energy use for heating is not metered and charged separately in multiple family dwellings, no significant fuel saving advantage accrues to those countries on this account. Support for the importance of the mode of metering is provided in a study of master metered versus individually metered apartments in the United States, where it was found that the master metered apartment dwellers consumed about 35 percent more electricity than those who paid for their own electricity use. [30] Separate metering of heating energy in multiple family dwellings is now being introduced in Europe; initial results are promising.

Per capita energy use for water heating is about the same in Sweden and the United States but is much lower in West Germany. In Germany spot water heaters—which are located at the point of use and heat water on demand—are widely used, while many apartments in Sweden have centralized hot water systems with no separate metering. The performance of the German system is suggestive. In principle, spot heating can be far more efficient because heat losses from hot water storage and transport are eliminated.

Air-conditioners and clothes dryers are essentially not used in Sweden and West Germany. Refrigerators are typically smaller and not frost free. Little data is available on lighting. Other appliances are not important energy users.

Data available on energy use in commercial buildings in Germany is sparse. Overall energy use in Swedish commercial buildings is 30 percent lower per unit of area than in the United States. Heating energy, corrected for floor space and climate differences, is, as in the residential sector, about one-half that of the United States. Tighter lighting standards in Swedish commercial buildings mean that air-conditioning for central cores of large buildings is not necessary in winter as it is in the United States.

B. Manufacturing Energy Use

Because the mix of industrial product differs among Sweden, West Germany, and the United States, and because energy consumption is much greater for basic materials production than for fabrication or other light manufacturing, care must be taken in making comparisons among these countries, even though all are heavily industrialized. For broad industrial categories, energy use per dollar of product is typically somewhat greater in Sweden and substantially less in Germany than in the United States. Swedish industry, however, is concentrated more in the production of basic materials—steel, cement, bulk chemicals, pulp, et cetera—than is American industry. When particular processes are compared, then German and Swedish practices are more efficient than in the United States. Compared with the United States, for example, steelmaking requires 85 percent as much fuel input per physical unit in Sweden and 68 percent in Germany. Paper manufacture requires 77 percent as much fuel in Sweden and 57 percent in Germany. Swedish performance in these areas is actually better than these figures suggest. In fact it is roughly com-

[3] Because the ratio of exterior surface area to floor area is less for multiple family dwellings.

parable to the German performance, because the primary fuel inputs are exaggerated in the Swedish case—where there is much use of hydropower—by nominally associating three units of fuel with each unit of electricity, and also because the Swedish paper industry makes extensive use of wastes for fuel. (Energy conversion efficiencies are often lower with wastes than with fossil fuels.)

Factors that contribute to the better energy performance of some basic Swedish and German industrial processes include more modern equipment, a tradition of minimizing obvious energy waste because of higher fuel costs, and more cogeneration of electricity and heat. Schipper and Lichtenberg assert that because of energy efficiency differences for specific manufacturing processes Swedish technology is 10 to 15 years ahead of corresponding U.S. technology.

Aggregate consumption of energy by industry per dollar of output depends on the mix and design of consumer products as well as the performance of basic industrial processes. We have seen no systematic comparison of the mix and design of products in Europe and the United States. The fragmentary evidence we have seen suggests that this is not the major factor in the lower industrial energy use per dollar characterizing Sweden and Germany.[4]

C. Energy Use in Transportation

The most striking statistic in this international comparison is found in the transportation sector: per capita energy use for passenger travel in the European countries is roughly one-fourth that of the U.S. (See table 5.) Auto travel—in passenger miles—is the dominant travel mode in all three countries, but the average distance each person travels annually in the European countries is roughly one-half that for the United States, and the energy use per passenger mile in the European countries is again about one-half that of the United States.

TABLE 5.—RELATIVE USE OF ENERGY FOR TRANSPORTATION IN SWEDEN, WEST GERMANY, AND THE UNITED STATES

[In percent of U.S. level]

	Sweden [1] (1970–72)	West Germany [2] (1972)
Passenger travel:		
Passenger-miles per capita	54	48
Fuel per passenger-mile [3]	52	52
Fuel per capita	28	25
Freight:		
Ton-miles per capita	[4] 45	21
Fuel per ton-mile	[4] 115	189
Fuel per capita	73	39

[1] Schipper and Lichtenberg, reference 26.
[2] Goen and White, reference 27.
[3] For automobiles only.
[4] Road and rail only.

[4] The detailed analysis in reference 25 of the various factors affecting industrial energy use in 9 different countries concludes, as we have here, that the high ratio of U.S. industrial energy consumption to output arises almost exclusively from high U.S. industrial energy intensities and not from structural factors.

The reduced level of travel in Germany and Sweden can be accounted for by the facts that the metropolitan areas are more compact (so that commuting distances are shorter) and that bicycling and walking instead of driving are relied on for short distances. The primary reasons for lower energy per passenger mile in Sweden are: Higher vehicle occupancy and better gas mileage. Better gas mileage, attributable mainly to lower auto weight is the most important single explanation of this superior performance. While public transportation is much more important in Sweden and Germany than it is in the United States, it has been too small a factor to affect overall transportation energy use greatly.

The greater use of energy per ton-mile for transporting freight in Germany (see table 5) probably reflects the fact that more freight is moved short distances by truck, while in the United States, coastal and inland water transport and pipelines are relatively more important.

D. The Relevance of European Experience for the United States

Comparison of specific uses of energy in Sweden and West Germany to those in the United States shows that both the use of better equipment and the prevalance of tasks demanding less energy account for the lower energy use in Europe. Better equipment seems evident in better housing insulation in Sweden; systems for cogenerating electricity and heat in municipalities (in some district heating systems) and in industry; and the general use of modern process equipment throughout industry. Examples of less energy demanding tasks include lower indoor temperatures in winter and, in Germany, zonal heating; clothes drying; and air conditioning other than by machine; lower lighting levels in commercial buildings; smaller cars; and reduced daily transportation needs arising because population is concentrated in small centers near work and shopping.

The existence of these differences in nations of comparable affluence and level of industrialization suggests some possibilities for reducing the energy/GNP ratio that are practical and could be adapted for the United States. Also some of the European policies that shaped energy saving practices may be relevant for the United States. The more important policy measures limiting energy demand in these countries include: Much higher prices for road fuel because of high taxes; excise taxes on large cars; enhancement of urban communities by zoning against sprawl-type expansion, and by maintenance of good public transport, and other public services; and assistance for industrial capital formation. The price mechanism has been used only for some energy forms. In Sweden prices much higher than those in the United States have tended to limit both road fuel and natural gas use, while the prices of heavy oils, heating oils, coal, and electricity have been comparable to those in the United States.

While much of the European experience provides valuable insights about possible future directions for the United States, the best prescription for change in the United States is not necessarily to adopt all Swedish and German experience. In some cases (e.g., clothes drying) many Europeans have clearly accepted a lower material standard than many Americans enjoy, suggesting that tradeoffs are associated with different levels of energy use for some activities. However, as we shall show below, it is in the areas where the differences between United States and European habits are most apparent that there are also the greatest opportunities for improved energy performance. As we shall show, existing and new technology could be used to provide the material amenities to which many Americans have become accustomed with much less energy use.

IV. TECHNICAL MEASURES FOR FUEL CONSERVATION

Macro-economic analyses suggest that in response to higher prices energy growth would be slower than it has been historically. But such analyses give no insights into how energy savings might be realized in specific applications. Moreover, macro-economic analyses involve looking at the future as an extension of past trends—a practice of questionable validity in light of recent very sharp departures from past trends—particularly in energy prices, as figures 3 through 5 show. A complementary and, we believe, more fundamental approach to understanding the potential for fuel conservation is to examine in detail for particular activities the way energy is used and to assess from a technological perspective the opportunities for reduced energy inputs.

A. Second-Law Efficiency Analysis

Fuel consumption associated with any activity or process is obtained by multiplying two factors:

$$\text{Demand for the product or activity} \times \text{Specific energy},$$

where specific energy is the energy required to perform the task of providing each unit of the product or activity. For example, the fuel used to drive automobiles is the product of the number of miles driven and the specific energy. The specific energy in this case is the average fraction of a gallon consumed per mile, the reciprocal of the familiar miles per gallon. Energy can be conserved both by curbing demand for energy-intensive activities and by reducing specific energies. The demand for products depends on considerations like personal goals, income, and the like. While changes in demand may be desirable in some areas, such changes depend on highly uncertain consumer attitudes. Here we will not speculate on how consumers might modify their behavior in the pursuit of energy conservation goals. Instead we focus attention on conservation opportunities associated with reducing the specific energies involved in providing goods and services—that is, on efficiency improvements.

We need to introduce a technological efficiency measure for energy-consuming processes which can be used to point up the possibilities for efficiency improvements. The energy conservation literature is peppered with discussions of the efficiency of energy use. Unfortunately, the efficiency concepts commonly used are entirely inadequate indicators of the potential for fuel savings. A couple of examples illustrate this point.

Household furnaces are typically described as being about 60 percent efficient, which means that 60 percent of the heat released in fuel combustion can be delivered as useful heat to the rooms. This measure suggests that a furnace which is 100-percent efficient would be the best you can do; this is incorrect, however, because devices exist for actually delivering more heat. A heat pump, which is an air conditioner operating in reverse, extracts energy from the out-of-doors and delivers it as heat at a useful temperature. In the process the out of doors is cooled, and more than 100 percent of the energy needed to run the heat pump is delivered as heat.

Air conditioners are rated by a coefficient of performance (COP), which is the heat extracted from a cooled space divided by the electrical energy consumed. A typical air conditioner might have a COP=2. Unfortunately this measure provides no hint as to how this performance compares to the maximum possible, which is a COP much greater than 2.

In these and other cases, efficiency is defined as

$$\frac{\text{desired energy transferred to the purpose of the system}}{\text{energy input to the system}}$$

Because it is based on the first law of thermodynamics, which holds that energy is neither created nor destroyed, this concept of efficiency is often called the "first-law efficiency." This efficiency concept enables one to keep track of energy flows and is thus useful in comparing devices of a particular type. However, it is wholly inadequate as an indicator of the potential for fuel savings. A much more meaningful efficiency is one which measures actual fuel consumption in relation to the theoretical minimum amount needed to perform a task. For example, in heating a house the task of the heating system might be to provide warm air to maintain rooms on a certain temperature schedule for a season, given particular heat losses from the house. The task of the engine and transmission of a car might be to maintain a 55-mile per hour speed for 1 mile, given the car's air drag and tire losses. The task determines the theoretical minimum fuel consumption without reference to the actual equipment used (that is, without reference to use of a furnace for heating or use of an internal combustion engine for a car). Thus we can define an efficiency as

$$\frac{\text{theoretical minimum fuel consumption for a particular task}}{\text{actual fuel consumption for a particular task}}$$

The minimum amount of fuel required to perform a task is determined by the second law of thermodynamics, so that this measure of efficiency has been called the "second-law efficiency."

To summarize, the fuel consumption associated with any particular product or activity can be expressed as the product of three factors

$$\begin{matrix}\text{Demand for the}\\ \text{product or}\\ \text{activity}\end{matrix} \times \begin{matrix}\text{Minimum fuel}\\ \text{consumption}\\ \text{for a unit task}\end{matrix} \times \frac{1}{\text{Efficiency}}$$

Here the efficiency is the "second-law efficiency."

The theoretical basis for doing second law efficiency calculations was provided in the pioneering work of physicist Willard Gibbs nearly 100 years ago. Unfortunately the diffusion time for this science into public policy applications has been long. Over the last several years Charles Berg [31] has advocated use of this concept in public policymaking. A study done for the Energy Policy Project [5] applied the concept to industrial energy use, and a recent American Physical Society study [32] estimated second law efficiencies in significant energy consuming areas throughout the economy. In table 6 we list typical second law efficiencies in significant energy-consuming areas. These values suggest that throughout the economy energy is used very inefficiently. For example, while the first law efficiency for a gas furnace (60 percent) gives the misleading impression that only a modest improvement is theoretically possible, the second law efficiency (5 percent) correctly indicates a twentyfold maximum potential gain.

TABLE 6.—*Second law efficiencies for typical energy-consuming activities*

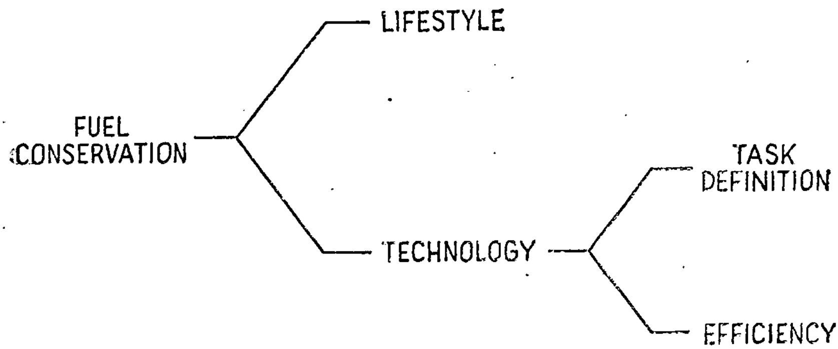
Sector	*Second law efficiency (percent)*
1. Residential/commercial:	
Space heating:	
Furnace	5
Electric resistive	2½
Air-conditioning	4½
Water heating:	
Gas	3
Electric	1½
Refrigeration	4
2. Transportation: Automobile	9
3. Industry:	
Electric power generation	33
Process steam production	32
Steel production	23
Aluminum production	13

Just how far can we expect to go toward achieving the theoretical maximum of 100 percent efficiency? In practice 100 percent efficiency is never achieved. This maximum is limited by both available technology and economics. At some point the fuel savings associated with a further efficiency gain are not worth the additional capital cost. Our judgment, which is based on the study of a variety of devices and processes, is that over the long term a goal of 20 to 50 precent is reasonable for ultimate practical systems. The values at the high end of this range would be more characteristic of highly engineered devices designed for specialized tasks (mainly in industry), and values at the low end would be representative of what could be achieved with more flexible, less sophisticated devices suitable for wide applications in our homes, in buildings, and in transportation. Thus there is considerable room for efficiency gains through innovation, starting from today's technology.

While this efficiency measure suggests potentially enormous opportunities for savings, it does not tell the whole story, because the efficiency given is for a specific task, which can often be modified without adversely affecting the quality of the product provided. For example, table 6 indicates that the second law efficiency for aluminum production is 13 percent. But this is the efficiency for producing aluminum from virgin ores, where the theoretical minimum energy requirement is 25 million Btu per ton of aluminum, compared to 190 million Btu used today. If the task is redefined to allow for recycling, the potential for fuel savings is even greater, since aluminum production from scrap requires less than 10 million Btu per ton. Similarly, for space heating, the efficiency listed in table 6 is for heating a building of given physical characteristics—characteristics that include the degree of insulation, whether or not there are storm windows, et cetera. Adding insulation and improving furance efficiency are complementary approaches to reducing fuel consumption.

The structure of the argument of this subsection is summarized by figure 17. One factor of energy consumption is the final demand, a matter, mainly, of lifestyle, discussed briefly in section II. The technological factor in energy consumption can be separated into two parts: A part that depends on task definition, which, in many cases, is subject to major technical improvement, and an efficiency. The concept of second law efficiency is useful for policy analysis because it is a factor whose scope for improvement is known: the maximum efficiency rating is one, and practical maxima are reasonably subject to estimation. In the next subsection we present examples of technologies with improved energy performance which could become widely available within the next decade or two.

FIGURE 17.—Factors into which fuel conservation activities can be analysed. In this paper emphasis is given to fuel conservation that can be achieved through use of improved technology.



B. ILLUSTRATIVE EXAMPLES OF CONSERVATION OPPORTUNITIES THROUGH TECHNICAL CHANGE

We have described elsewhere [33] fuel conservation opportunities in four illustrative areas which together account for 40 percent of total U.S. energy use: The automobile, residential space heating, commercial air-conditioning, and industrial process steam. In each case the potential savings that could be achieved over the next 10 to 15 years are estimated. Here we only brlefly highlight the principal results.

In the case of the automobile, presently available technology could be introduced in the next couple years to boost average fuel economy in new cars to over 20 miles per gallon with only a modest reduction in auto weight, say 20 percent. Going further, technological innovations like new engine designs—lightweight diesel, Rankine, or Stirling—and improved transmissions, could lead to an average fuel economy of 30 to 35 miles per gallon for new cars after a decade or so. Of course, these goals have already been achieved with small cars.

In the area of space heating, modest innovations in design and development of new devices and materials, such as better windows and improved insulation to reduce both heat conduction and air infiltration, could cut heat losses in homes by nearly 75 percent. Such a reduction has far-reaching implications for the heating system, because, except for very cold days, no supplemental heating beyond what is provided by sunlight through the windows, the electric load, and body heat would be needed. But even further savings possibilities exist for days when modest supplemental heating is needed. A small electric heat pump that uses well water or lake water as a heat source would be twice as efficient in providing heat as a gas furnace.

It may come as a surprise that, in the case of commercial air-conditioning, heat from lighting is often the largest component of the air-conditioning load, accounting for up to 60 percent of the total. Here, substantial savings can be achieved by adopting task-specific instead of uniform lighting strategies now often employed and by turning off lights when they are not in use. In new buildings, greater use of natural lighting could be achieved. After lighting, the next largest component of the air-conditioning load is typically the cooling requirement for the ventilation system. While a certain amount of outside air is needed to control odors, to keep carbon dioxide levels down, and to provide adequate oxygen, typical ventilation rates are far in excess of what is required. Moreover, the use of heat exchangers in the ventilation system could substantially reduce the air-conditioning requirements for the fresh air that is needed. With reduced use of lighting, an improved ventilation system, and more insulation, air-conditioning demand could often be reduced to less than one-third of its present level. With this greatly reduced air-conditioning demand, it becomes feasible to think of meeting a substantial fraction of the energy requirements for air-conditioning in a commercial office building with solar energy. Heat-driven refrigeration devices are presently widely used to provide air-conditioning for large buildings. Solar-assisted, heat-driven air-conditioners may well be commercially available within a decade. Implementing all these innovations could cut fuel requirements for air-conditioning in a typical New York City office building to one-sixth of what they are now.

In producing steam today for industrial process heat uses, fuel is burned to boil water much as one boils water in a kettle. While the first law efficiency for this process is an impressive 85 percent (that is, 85 percent of the fuel energy ends up in the steam), the second law efficiency is typically a much more modest 32 percent. The usual process of steam generation wastes the high quality energy in fuel. If, instead, the combustion energy of the fuel is used first to produce electricity, with the "waste heat" from power generation utilized as process steam, the second law efficiency of combined electricity and steam production could be increased to 40 or 45 percent, compared to an efficiency of about 33 percent for the separate production of steam and electricity. The resulting fuel savings are actually much more impressive expressed another way: If only the excess fuel beyond what is required for steam production is attributed to electricity generation, the fuel required to produce 1 kilowatt hour of electricity is reduced to about half of that required in conventional powerplants. At the national level, the potential fuel savings from the cogeneration of electricity and process steam is truly great, because process steam is a major energy-consuming activity in the economy, accounting for about 14 percent of total U.S. fuel consumption.

The most promising application of steam-electricity cogeneration appears to be in industrial plants, where electricity could be produced as a byproduct whenever steam is needed. Various cogeneration technologies could be employed. In a steam-turbine system, steam used to drive the power-generating turbine would be exhausted from the turbine at the desired pressure and (instead of being condensed with cooling water, as at a conventional powerplant) delivered to the appropriate industrial process. With a gas-turbine system, the hot gases exhausted from the power-generating turbine would be used to raise steam in a waste heat boiler. The gas-turbine system is the more efficient of the two, typically with a second law efficiency of 45 percent, compared to 40 percent for a steam-turbine system; in addition, because it produces several times as much electricity for a given steam load, the gas-turbine cogeneration system could yield several fold greater total fuel savings than the steam-turbine system.

Recent studies on the overall potential for cogeneration have been carried out by Dow Chemical Co. [34] and by Thermo Electron Corp. [35] The latter's study shows that by 1985, electricity amounting to more than 40 percent of today's U.S. consumption (generated with about 135,000 megawatts electrical of equivalent baseload central station generating capacity) could be produced economically with gas turbines as a byproduct of process steam generation at industrial sites. Through displacement of conventional central station generating capacity that would otherwise be built, the fuel savings would amount to about 5 percent of the present level of U.S. energy consumption. (While the gas turbines in use today must be fueled with gaseous or liquid fuels, it is likely that over the next decade high-pressure fluidized-bed combustors will be available as an economic method of firing gas turbines directly with coal. [36])

To produce power most economically, an industrial installation that generates electricity as a byproduct of process steam production would often produce more electricity than could be consumed onsite. Thus the cogeneration unit should be interconnected with a utility and could substitute for some central-station baseload generating capacity. But such an arrangement is often difficult under existing utility policies. Considerable modification of utilities' transmission, control, and perhaps storage systems may be necessary if interconnected cogeneration capacity is developed on a large scale.

The production of process steam as a byproduct of power generation at large central station powerplants is an alternative to cogeneration at industrial sites. However, such steam production does not lead to a significant increase in second law efficiency, since there is very little useful work left in the powerplant cooling water, which has an average temperature of about 100° F. If the waste heat is to be useful for industrial processes, powerplant operations would have to be modified to produce heat at more useful temperatures (200° to 400°F.). But this would reduce the electrical output, and this change could lead to a net loss of overall efficiency unless essentially all the heat were put to effective use. Not only are the potential gains of byproduct steam generation small, but there are serious implementation difficulties as well. Because it is uneconomic to transport steam long distances, steam-using industries would have to be near the powerplants from which their heat is supplied, and this is a condition often difficult to fulfill. There is also a serious mismatch in time: Large central-station powerplants require 6 to 10 years for construction and are designed for a quarter century or more of service. For these reasons, cogeneration at industrial sites is favored.

C. The Fuel Conservation Potential for the Economy Today

We turn now to estimating the potential fuel savings from pursuing fuel conservation measures throughout the economy. Because we wish to focus on what can be implemented on a wide scale within roughly the next two decades, the proposals taken into account are somewhat less ambitious than some of those discussed in the previous subsection. Tables 7a, 7b, 7c, and 7d show the potential savings which would have been achieved in 1973 had the set of indicated conservation technologies been implemented. The potential savings for the economy as a whole are summarized in figure 18, where actual and "hypothetical" energy budgets for 1973 are compared. It is seen that the hypothesized technical change, providing the same products as in 1973, would have reduced energy consumption from 75 quads to 44 quads. In other words if the fuel conservation measures considered here had been in effect in 1973, fuel consumption would have been less than 60 percent of its actual level. These savings are in addition to what could also be achieved through measures involving changes in lifestyle—a heavy shift to small cars, enforced 55 miles-per-hour speed limits, lowered thermostats in the winter, and the like.

TABLE 7a.—*Potential annual fuel savings in the residential sector* [1]

[In 10^{15} Btu]

Conservation measures	*Potential savings*
Replace resistive heating with heat pumps having a coefficient of performance (COP) of 2.5 [2]	0. 60
Increase air-conditioning COP to 3.6 [3]	. 40
Increase refrigerator efficiency 30 percent [4]	. 27
Cut water heating fuel requirements in half [5]	1. 07
Reduce heat losses 50 percent with better insulation, improved windows, reduced infiltration [6]	3. 30
Reduce air-conditioning load by reducing infiltration to 0.2 air exchanges per hour [7]	. 42
Introduce total energy systems into ½ multfamily units (15 percent of all housing units) with a net 30 percent fuel savings [8]	. 31
Use microwave ovens for ½ of cooking, with 80 percent savings [9]	. 25
Total savings [10]	6. 62
Actual fuel use in 1973	14. 07
Hypothetical fuel use with conservation	7. 45

[1] In tables 7a–7d the potential savings associated with a particular conservation measure sometimes depend on the previously listed measures. For example, the savings associated with a reduced air-conditioning load is affected by the previous assumption that all air-conditioners are more efficient.

[2] APS, sec. 3.C.2.

[3] According to reference 43, the best room air-conditioning units have a COP twice as large as the present average 1.S. Also some commercial central air-conditioning units have a COP of 3.6. We assume the present average is 2.5 for central air-conditioning.

[4] Recently Hirst has shown [55] that a 52-percent energy saving would result from implementing a set of conservation measures that would increase the cost of a 16 cubic foot frost-free refrigerator 19 percent.

[5] Current efficiencies are low (APS, sec. 3.D). There are various possibilities for reducing losses: better insulation, reduced hot water heater temperature setting, use of solar energy or heat recovery from other appliances such as refrigerators.

[6] APS, sec. 3.B.

[7] APS, sec. 3.C.1.

[8] APS, sec. 3.E.

[9] Reference 44, p. 60.

[10] Hirst has analyzed fuel use by the residential sector in terms of a variety of scenarios for the period to the year 2000. [56] In his conservation scenario fuel use drops about 25 percent per household. In our analysis we have projected a reduction in fuel use of 47 percent per household. The major difference between the two estimates is associated with assumptions relating to heat losses by buildings, especially single-family houses; our assumed improvements are more ambitious than those of Hirst who adopted the relatively modest 1975 guidelines of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Hirst states that "energy savings much higher than these estimated . . . can be achieved in a cost-effective manner."

TABLE 7b.—*Potential annual fuel savings in the commercial sector*[1]

[In 10^{15} Btu]

Conservation measures	*Potential savings*
Increase air-conditioning COP 30 percent	0.37
Increase refrigeration efficiency 30 percent	.20
Cut water heating fuel requirements in half	.31
Reduce building lighting energy by 50 percent:	
Direct savings [2]	.82
Increased heating requirements [3]	−.21
Reduced air-conditioning requirements [4]	.34
Net savings	.95
Reduce heating requirements 50 percent [5]	2.25
Reduce air-conditioning demand 10 percent with better insulation [6]	.08
Reduce air-conditioning demand 15 percent by reducing ventilation rate 50 percent (to 0.5 air exchanges per hour) and by using heat recovery apparatus [7]	.10
Use total energy systems in ⅓ of all units—save 30 percent	.64
Use microwave ovens for ½ of cooking	.06
Total savings	4.96
Actual fuel use in 1973	12.06
Hypothetical fuel use with conservation	7.10

[1] In this analysis the entire commercial sector is treated as though it were commercial building operations.
[2] APS, section 3.C.4.
[3] Assume that for 6 winter months all lighting electricity saved must be replaced by fossil fuel heat.
[4] According to reference 45, p. 171, lighting in a typical New York City office building accounts for about 54 percent of the air-conditioning load. We assume this is typical.
[5] Reference 45, p. 168.
[6] Reference 45, pp. 170–171.
[7] Reference 45, pp. 171–172.

TABLE 7c.—*Potential annual fuel savings in the industrial sector*

[In 10^{15} Btu]

Conservation measures	*Potential savings*
Good housekeeping measures throughout industry (except for feedstocks), save 15 percent [1]	3.85
Fuel instead of electric heat in direct heat applications [2]	.17
Steam/electric cogeneration for 50 percent of process steam [3]	2.59
Heat recuperators or regenerators in 50 percent of direct heat applications—save 25 percent (references 31 and 5)	.74
Electricity from bottoming cycles in 50 percent of direct heat applications	.49
Recycling of aluminum in urban refuse [4]	.10
Recycling of iron and steel in urban refuse [5]	.11
Fuel from organic wastes in urban refuse [6]	.70
Reduced throughput at oil refineries [7]	.87
Reduced field and transport losses associated with reduced use of natural gas [8]	.80
Total savings	10.43
Actual fuel use in 1973	29.65
Hypothetical fuel use with conservation	19.22

[1] According to references 46 and 47, savings on this order should be possible with better management practices and no changes in capital equipment.
[2] At this point no savings are attributed to the use of recuperators, etc.; we assume that only 50 percent of the energy value of the fuel goes to process. See reference 46.
[3] This in addition to the 14 percent of process steam now associated with byproduct electricity. Here various cogeneration schemes were considered. See references 34, 35, and 36.
[4] Assumes recovery of 0.75 million tons of aluminum from urban refuse, reference 48, saving 135 million Btu/ton. This assumes the efficiency improvement in producing primary aluminum estimated in reference 5; otherwise the savings would be 180 million Btu/ton.
[5] Assumes recovery of 10.6 million tons of iron and steel in urban refuse, reference 48, saving 10.4 million Btu/ton. This assumes the efficiency improvement in producing steel from virgin raw materials estimated in reference 5.
[6] Assumes 75 percent recovery of organic wastes and a 70-percent conversion efficiency to a suitable fossil fuel supplement, reference 49.
[7] On the basis of refinery fuel consumption at a rate of 10 percent of output, reference 5. This takes into account fuel conservation opportunities in petroleum refining.
[8] Assuming 6.3 percent of gas is consumed in oil and gas fields and 3.3 percent is consumed in pipelines, reference 50.

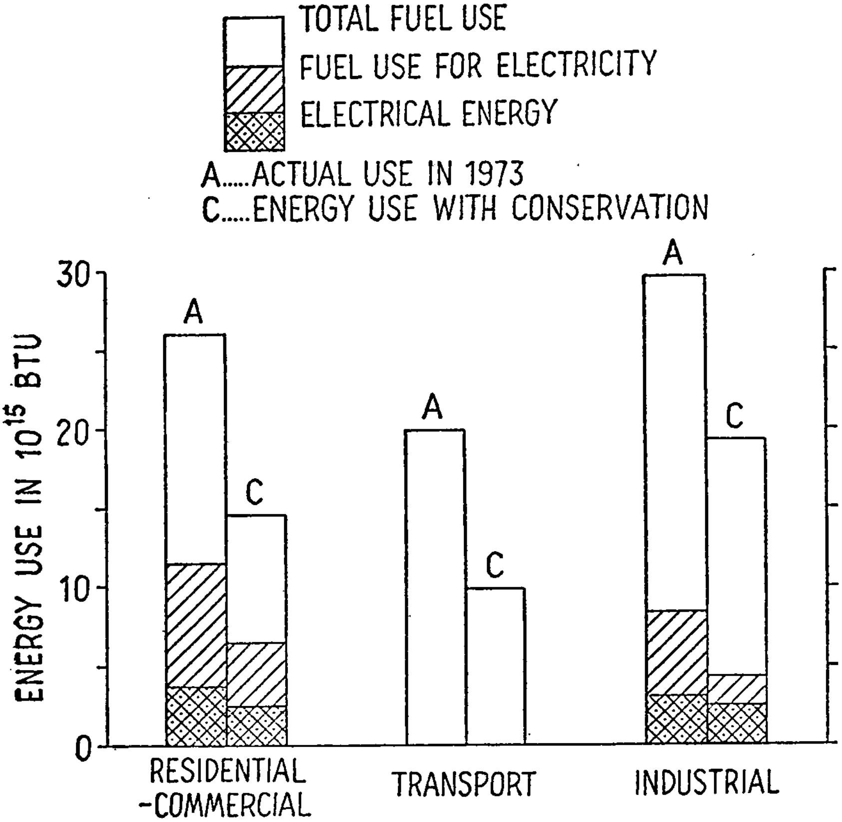
TABLE 7d.—*Potential annual fuel savings in transportation*

[In 10^{15} Btu]

Conservation measures	*Potential savings*
Improve auto fuel economy 150 percent [1]	5.89
35 percent savings in other transportation areas	3.20
Total savings	9.09
Actual fuel use in 1973	18.96
Hypothetical fuel use with conservation	9.87

[1] APS, section 4.G.

FIGURE 18.—Summary of the fuel saving potential in the various energy consuming sectors detailed in Tables 7a–d. The savings are associated with technical change alone. The goods and services provided by energy in the hypothetical economy would be the same as in the actual economy for 1973.

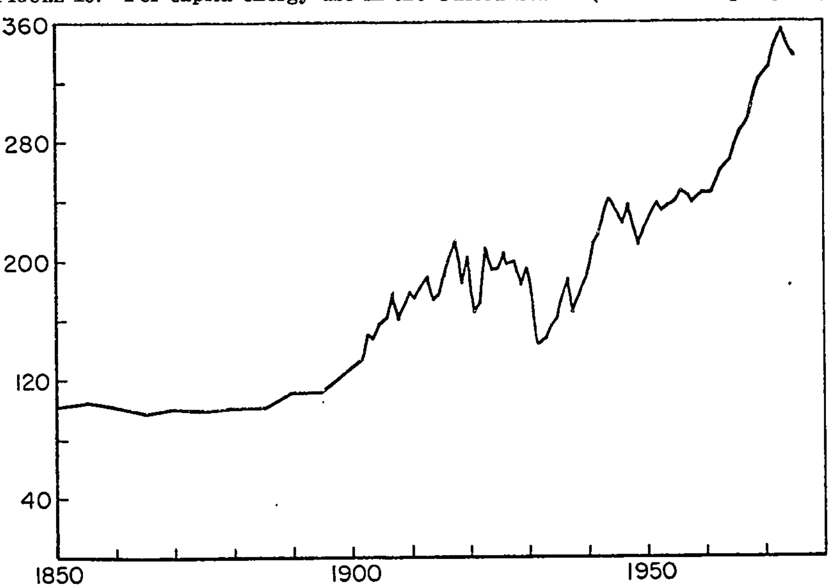


Looking beyond the program implied by tables 7a to 7d we can get a rough idea of further opportunities for conservation from the second law efficiencies associated with these improvements. In the residential, commercial, and transportation sectors, the efficiencies still would be relatively low (typically in the range 8 to 15 percent, compared to 2 to 10 percent today). This suggests that opportunities still will exist for substantial further improvements through technological change. However, for energy intensive activities in the industrial sector, operations may well be approaching the practical limits to efficiency improvement. This suggests that further industrial fuel savings would depend mainly on shifting the industrial product mix toward less energy intensive products.

If the degree of technical improvement represented by the fuel savings shown in figure 18 were accomplished over the remainder of this century, the rate of decline in the E/GNP ratio would be about 2.3 percent per year faster than the long-term historical rate. Since, as we have shown in section II.D, energy consumption following "historical trends" would grow no faster than 2.3 percent per year in the period 1985 to 2000, the result of pursuing these fuel conservation measures would be zero energy growth beyond 1985. Since the "historical trends" projection is based on the optimistic assumptions of sustained full employment and a return to a high rate of growth in labor productivity, the efficiency improvement rate assumed here is roughly the maximum rate needed to achieve zero energy growth in a vigorously expanding economy. Opportunities for substantial technological innovation are not reflected in this estimate; pursuing these opportunities would enable a continuation of zero energy growth, or even negative energy growth, for the period near the turn of the century and beyond.

This result that in the future zero growth in energy use could be compatible with maintaining a strong economy will not be readily accepted by those who believe firmly in the persistence of historical trends. However, it is worth noting that the historical growth in energy use has not been so persistent as most people think. Figure 19 shows the long-term record of per capita energy use in the United States. What we find remarkable about these data is that, while certain periods have been characterized by rapid growth in per capita energy use, there also have been long periods where per capita energy use has grown hardly at all. Thus the historical record itself provides evidence that "trend is not destiny."

FIGURE 19.—Per capita energy use in the United States (million Btu per year).



Source: "Historical Statistics of the United States," and U.S. Bureau of Mines news releases.

D. The Role of Electricity

Electricity has had a special role in projections of energy use. Historically electricity consumption has grown about twice as fast as total energy consumption. Most energy forecasts envision that the trend toward electrification will continue. However, as we have pointed out, the principal driving force for the trend toward electrification, the historical pattern of rapidly declining prices for electricity relative to other energy forms, has been dissipated. In light of the new energy realities projections of electricity growth should be reevaluated.

The analysis in the previous subsection suggests that efficiency improvements in the economy as a whole would involve continuation of the trend toward electrification. As shown in table 8, the savings associated with the conservation measures envisioned in table 7 correspond to a 30-percent reduction in electricity use, while total energy use would be reduced more than 40 percent. The result that the proportional savings for electrical end uses should be less than for other fuel forms is what one might expect from inspection of the data in table 6, which shows that the generation of electricity, even at a central station powerplant, is a relatively efficient process compared to most other energy activities in the U.S. economy. This contradicts the common notion that the generation of electricity is inefficient, "wasting" 2 Btu of fuel for each Btu of electricity produced; this notion ignores the fact that electricity is energy of the highest quality, while the waste heat is low grade thermal energy. It is only for certain ultimate uses that do not make effective use of this high quality energy that the overall efficiency of fuel use via electrification is low. (A prime example of this waste is electric resistive heating, for which the second law efficiency is only about 2½ percent.)

TABLE 8.—SUMMARY OF ENERGY SAVINGS (IN 10^{15} BTU PER YEAR) DETAILED IN TABLES 7a TO 7d [1]

	Primary fuel energy		Electrical energy	
	Amount	Percent	Amount	Percent
Actual use	74.8	100	6.7	100
Savings	31.1	42	2.0	30
Hypothetical use	43.7	58	4.7	70

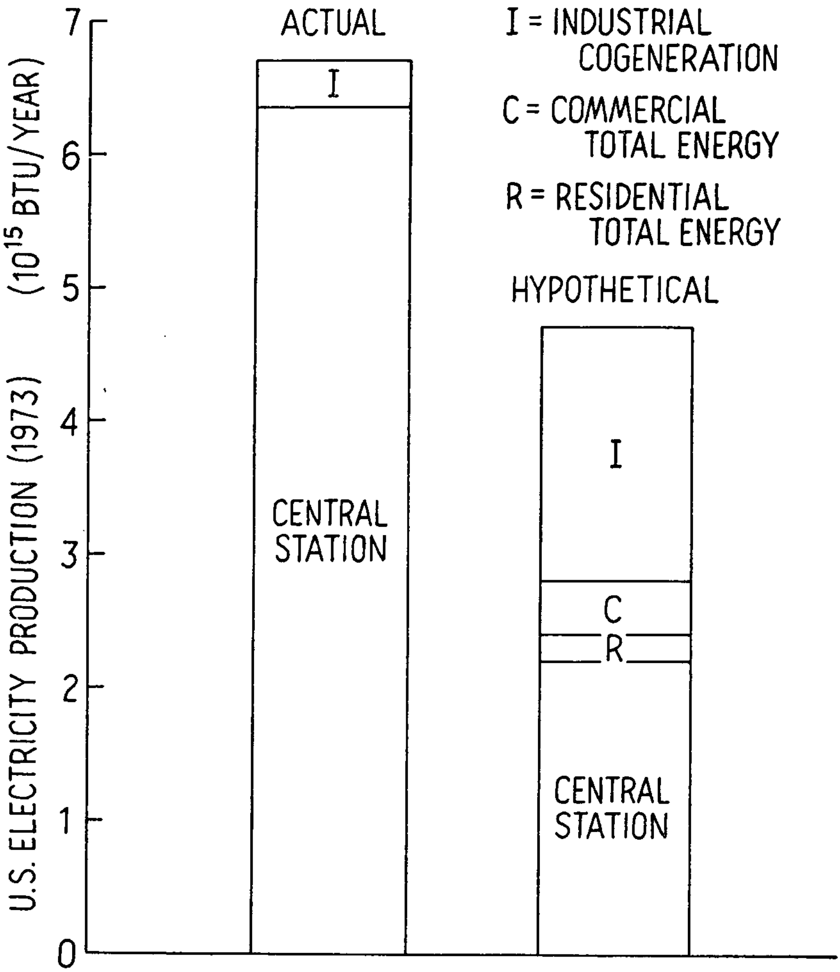
[1] The savings are associated with technical change alone. The goods and services provided by energy in the hypothetical economy would be the same as in the actual economy for 1973.

A continued trend toward electrification would be compatible with the achievement of fuel conservation goals only if the electrical energy is effectively utilized. Some current projections of electrical energy growth involve substantial ineffective uses. For example, ERDA's "intensive electrification" scenario [37] involves growth in central station electricity production of 5½ percent per year to the year 2000. In this projection more electricity would be used for resistive heat in in industrial process applications in 2000 than is used today for all purposes. [38] Such applications involve a gross waste of fuel. Such a high growth rate for electricity consumption is not compatible with the trend toward more effective fuel utilization.

Nevertheless, pursuit of the conservation goals we have described would lead to greater growth in electric power use than in energy growth overall. Let us examine this growth from the supply viewpoint. The new dispersed electrical generating capacity (mainly industrial cogeneration) implicit in the hypothetical energy conserving economy of 1973 is equivalent to about 40 percent of the actual 1973 capacity. (See figure 20.) In addition, a considerable amount of new central station generating capacity—planned long before the 1973–74 energy crisis and designed to accommodate historical electrical demand growth through 1980 or so—is already under construction. Central station plants now under construction, together with the new dispersed generation capacity, would make possible, after the retirement of old plants, more than a 50-percent increase in electric energy production between 1975 and the year 2000. While this is much less than the growth anticipated by ERDA, [37] it is difficult to envision how a larger amount of electricity could be effectively utilized, even with a more modest conservation program than the one put forth here.[1]

[1] It is also worth noting that, with this rate of electricity growth, a 2-percent annual growth in the real price of electricity (see sec. II.B) and a 3.2-percent growth rate for real GNP (see sec. II.D), the fraction of GNP spent of electricity would grow at about the long-term historical rate. In this sense electricity growth at this rate would correspond to "historical growth" conditions.

FIGURE 20.—U.S. electricity production in 1973 according to the mode of production: Central station powerplants or dispersed cogeneration and total energy systems. The hypothetical electricity production for 1973 is based on the technical changes indicated in tables 7a, 7b, and 7c. The goods and services provided by energy in the hypothetical economy would be the same as in the actual economy for 1973.



Thus one effective fuel conservation strategy for the next couple of decades would be to "stretch out" the construction schedules for central-station powerplants already under construction, to postpone initiation of additional central-station plants, and to accommodate most further growth with decentralized power sources like industrial cogeneration. An attractive feature of this strategy is that it would be much easier than with large central-station power alone to balance electricity supply with demand in the new era when demand will be especially hard to predict. This flexibility of supply arises because cogeneration units would be small, having from 1 to 10 percent of the capacity of contemporary central power stations. Their manufacture and installation would be standardized. They would require only a couple of years to bring on line, compared to 6 to 10 years for central-station plants. Thus plans for new supply could be continually adjusted as one sees how demand is evolving, and the high costs of overcapacity could be avoided.

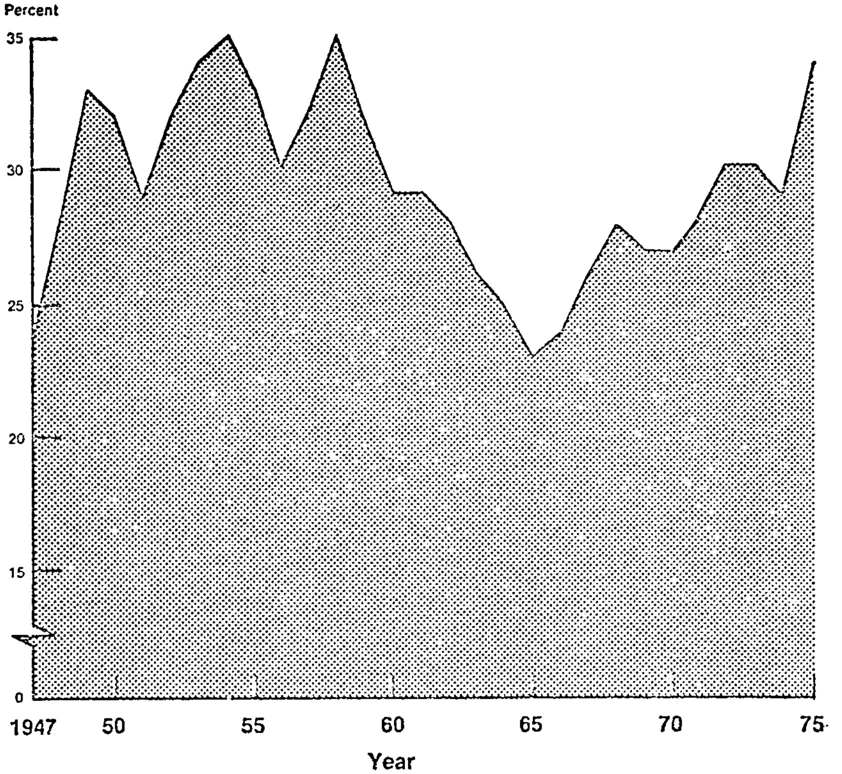
V. FINANCING FUEL CONSERVATION

In the previous section we argued that a substantial reduction in energy use could be realized in the U.S. economy through the adoption of economically justifiable fuel saving technology without curbing demand for the goods and services provided by energy. Yet there is no evidence of a rush to capture these savings. In part, of course, this merely reflects timelags in the decisionmaking process. The era of high-priced energy is just beginning, so that the use of energy is still determined largely by the stock of inefficient energy-using equipment left over from the era of low-priced energy. In part this also reflects the facts that many consumers are unaware of fuel-saving opportunities and that many conservation technologies are not widely available commercially. In addition, financing for economically sound conservation measures is often not available. In this section we will discuss the financing of fuel conservation and suggest policies for facilitating investments in economical projects.

In assessing the economics of fuel conservation two factors should be considered: (1) The capital requirements for saving fuel relative to the capital requirements for new fuel supplies, and (2) lifecycle costs of the two alternatives.

Knowing the capital requirements for fuel conservation is important from a national perspective because the energy supply industry is so capital intensive. Historically it has required about 30 percent of all new plant and equipment expenditures. (See Fig. 21.) With the continuation of energy growth as envisioned by ERDA in 1976, this share of business capital can be expected to increase, unless the share of GNP committed to business capital investment increases significantly from what it has been historically. [38] How will energy conservation policies affect the demand for capital? Will saving energy require more or less capital than producing new supplies?

FIGURE 21.—Energy's annual share of business plant and equipment investment.



Source: Reference 42.

The lifecycle cost (the cost of the initial investment plus expected future operating cost appropriately discounted to present value) is an important consideration for the consumer, since a conservation investment saves him money when the lifecycle cost of his energy investment is reduced.

A. Capital Requirements: Conservation Versus New Supplies

Providing new energy supplies is very costly. It has been estimated [1] that new offshore oil production and refining costs some $15,000 per barrel per day of new capacity [39] and that nuclear and coal-fired powerplants ordered today would cost about $700 and $400 respectively per kilowatt of electrical output capacity. [40] It is with such numbers that the capital requirements for conservation must be compared to estimate the relative capital intensities of new supplies and conservation. For such comparisons a common measure must be established. We have found it useful to specify energy supply investments per average rate of primary fuel consumption, so that in a given energy-consuming process the corresponding cost for conserva-

[1] All costs here are in 1974 dollars unless otherwise indicated.

tion would be the extra investment required per average rate of primary fuel saving. On this basis we compare, in table 9, the capital costs for a number of conservation measures with corresponding supply costs, expressed as dollars per thermal kilowatt (kw(t)).[2] These calculations suggest that there would be considerable net capital savings associated with many fuel conservation measures.

Most of the industrial examples of fuel conservation shown in table 9 fall under the rubric "cascading," which leads to large savings of both fuel and capital. Cascading refers to making successive use of heat energy as the temperature of the heat falls from the combustion temperature to the near ambient temperature at which the heat is ultimately disposed of in the environment. In the case of "bottoming cycles" (items 1–3) some of the moderate temperature heat rejected from industrial processes requiring high temperature heat is converted to electricity. Item 4 is similar in that heat ordinarily rejected from a process at moderate temperature is partially recovered for useful purposes. In all these examples where cascading is employed the capital costs for conservation are low relative to those for the equivalent new supplies, in part because the capital costs can be shared among the associated activities.

TABLE 9.—CAPITAL COST COMPARISONS FOR SELECTED ENERGY CONSERVATION MEASURES

Item	Capital investment for— Conservation compared with existing system (per kilowatt thermal) [1]	Capital investment for— Equivalent new supply (per kilowatt thermal) [1]
Residential:		
1. Heat pump replacing electric resistive heat plus central air-conditioning	[2] $50–$120	[7] $480–$650
2. Retrofit house with insulation and storm windows	[3] 450	[4] 275
3. Annual cycle energy system [1] replacing electric resistive heat plus central air-conditioning [5]	560	[7] 480–650
Industry: [6]		
1. Bottoming cycles [1] for industrial waste heat streams	160	[7] 480–650
2. Bottoming cycles [1] for stationary diesel engines	400	[7] 480–650
3. Bottoming cycles [1] for stationary gas turbines	225	[7] 480–650
4. Recuperators [1] for direct combustion furnaces, boilers, etc.	100	[4] 275
5. High consistency head-box formers for papermaking	45	[4] 275
6. Trough kiln for cementmaking	295	[4] 275

[1] See text for discussion.
[2] Based on the analysis in reference 51 for a COP of 2.7.
[3] For a wood frame house requiring 6,000 degree days of heating and no cooling. Other house characteristics are given in table 5.3 of reference 52. The capital cost calculation is based on the analysis in this report.
[4] Capital costs for production and refining of offshore oil have been estimated to be $15,300 per barrel per day of capacity (see reference 39) or $19,000 per barrel per day of input, for 12.6 percent energy losses (see reference 5) and an average capacity factor of 90 percent. Since 1 barrel per day equals 71 kW this becomes $275 per kilowatt thermal.
[5] The capital costs for the ACES are based on the data in table 10.
[6] The capital cost estimates for industrial conservation measures are based on estimates presented in reference 53. Estimates given there for capacity were divided by a capacity factor of 0.75 to give the capital requirements for the average fuel savings rate.
[7] From reference 40 we obtain capital costs (in 1974 dollars) of $400 per kilowatt electrical and $700 per kilowatt electrical for coal fired and nuclear plants respectively, coming on line in the early 1980's To this we add $500 per kilowatt electrical for transmission and distribution facilities, according to reference 39. The capacity factor is taken as 65 percent, for both coal and nuclear plants. Both thermal losses in generation and transmission losses are taken into account in estimating the capital cost per thermal kilowatt.

The total capital savings for the economy resulting from the implementation of conservation technology can be enormous. For the

[2] To convert from other common units to thermal kilowatts the following approximate conversion factors are appropriate:
1 barrel of oil per day equals 71 kw(t)
1 ton of coal per day equals 295 kw(t)
1,000 cubic feet of natural gas per day equals 12 kw(t)
For purposes of table 9, 1 kilowatt of electric power consumed corresponds to about 3 thermal kilowatts.

industrial sector, the recent Thermo Electron study [35] discussed in section IV.B above compares the total capital requirements for producing electricity via cogeneration to those for producing the same amount of electricity at central station powerplants, taking account of capital requirements for fuel supply as well as for the generation, transmission, and distribution of electricity. The Thermo Electron study estimates that, if gas turbines are used as the principal technology for cogeneration, building cogeneration capacity equivalent to 135,000 Mw(e) of central-station capacity would require some $90 billion (1976 dollars) of capital investment, whereas the central station alternative is estimated to require $131 billion.

While no detailed study yet has been made of the total capital requirements for conservation versus supply measures throughout the economy, one estimate provided by the Ford Foundation's Energy Policy Project [23] is that slowing energy growth from 3.4 to 1.9 percent through the year 2000 through energy efficiency improvements would require about $500 billion in capital for fuel conservation investments, compared to $850 billion for an equivalent amount of new energy supplies in this period.

B. Life-Cycle Costing

In table 9 three conservation measures appear to require investment comparable to or greater than corresponding options for bringing forth new energy supplies: Use of a trough kiln for cementmaking, retrofitting homes with insulation and storm windows, and installation of an annual cycle energy system. But even in the case of these capital intensive activities, the consumer would save money because the life-cycle costs are less with the conservation option than with the conventional energy system. We now illustrate this point with a description of the life cycle economics of the annual cycle energy system.

The annual cycle energy system is a technology under development at the Oak Ridge National Laboratory, [41] which would meet space conditioning and water heating demand through use of a heat pump that draws on a large insulated tank of ice water as a heat source. Because the heat source is an ice water mixture it can be maintained at 32° F year round. Throughout the winter the heat pump extracts heat from the water for space and water heating purposes, thereby freezing the water in the storage tank. The stored ice then provides air-conditioning in the summer.

Because the heat pump operates only on the heating cycle [3] and between constant temperature heat source and sink, and because it is easier to extract heat from water than from air, it can be designed to be about 75 percent more efficient than a conventional heat pump that uses outside air as a heat source. (It would have a COP of 3.5 using today's technology, compared to 2 for a conventional heat pump.) Also since storage of "coolth" becomes a byproduct of winter heating, additional electricity consumption for summer air-conditioning is all but eliminated. This not only leads to further energy savings but also means the air-conditioning does not contribute to the peak load of the electric utility. (Air-conditioning loads have caused many utilities in the United States to become summer peaking systems.)

[3] A heat pump can be operated in reverse as an air-conditioner in the summer.

Characteristics of this system and a conventional system for use in a garden apartment complex in Washington, D.C., are compared in table 10. These calculations show the remarkable result that the annual cycle energy system is estimated to reduce electricity consumption to less than 25 percent of what it would be with a resistive heat/electric air-conditioning system or to less than 30 percent of what it would be with space conditioning based on use of conventional heat pumps. The investment required for this system would be about three times that needed for a resistive heat/electric air-conditioning system or about twice that required for a conventional heat pump system. Nevertheless the discounted life cycle cost of this system to the consumer would be less than 60 percent of the annual cost of a conventional system, as shown in table 10.

TABLE 10.—CHARACTERISTICS OF ACES VERSUS CONVENTIONAL SYSTEM FOR GARDEN APARTMENTS IN A WASHINGTON, D.C., CLIMATE [1]

	Resistive heat plus air-conditioning	Conventional heat pump	Annual cycle energy system
Equipment performance:			
Heating COP		2.0	
Cooling COP	1.9	1.9	
Capital costs, installed (per apartment):			
ACES mechanical equipment			$1,880
ACES ice storage bin			1,328
Electric furnace, 14.4 kw	$420		
Electric air-conditioning, 30,000 Btu per hour	570		
Air-to-air heat pump, 30,000 Btu per hour		$1,500	
Electric water heater, 42 gal	100	100	
Total	1,090	1,600	3,210
Annual energy consumption (kilowatt-hour per year):			
Heating	5,830	2,910	
Cooling	3,170	3,710	
Water heater	3,870	3,870	
Total	12,870	9,950	2,920
Energy savings over resistance heat (percent)	0	23	77
Annual costs:			
Fixed charges at 11.8 percent [2]	$129	$189	$378
Maintenance	47	77	81
Electricity at 8.4 cents per kilowatt-hour [3]	1,082	836	246
Total	1,258	1,102	705

[1] This table is based on material in reference 41.

[2] The annualized fixed charge includes the mortgage payment for a 20-yr loan at 9 percent interest; the levelized equal annual payment on the investment equity (a 20-percent downpayment is assumed, for which the homeowner's personal discount rate is assumed to be 6 percent); a property tax of 3 percent per year on the initial investment; a property insurance rate of 0.4 percent per year on the initial investment; and a tax rebate appropriate for the 25-percent incremental income tax rate.

[3] In reference 41 the price of electricity is incorrectly taken as the present price of electricity, which is about 4 cents per kilowatt-hour for the U.S. eastern seaboard. If the electricity price increases at a rate r_e and the general inflation rate is r_i, then the average annualized price over the period T should instead be

$$\frac{r_i}{r_e-r_i}\times\frac{e^{(r_e-r_i)T}-1}{1-e^{-r_iT}}\times 4 \text{ cents per kilowatt-hour,}$$

which becomes 8.4 cents per kilowatt-hour for T=20 years with a general inflation rate of 6 percent and an inflation rate of 8 percent per year for electricity.

C. Policies for Financing Conservation

These calculations point up the importance of capital for effective energy conservation. Unfortunately, consumers who are likely to benefit most from these savings—typically homeowners and small businesses—do not always have ready access to the funds needed for these investments. These consumers usually have limited credit for energy conservation investments or must pay high interest rates if they are fortunate enough to be able to borrow. In contrast, many of the corporations that supply energy not only can use their high profits and internal cash flows but also can attract outside capital much more easily than many energy consumers, often at the prime interest rate.

A good case can be made that policies to facilitate fuel conservation investments would be in the national interest. For a given level of economic activity, both overall business capital outlays and total expenditures for energy could be reduced with a strong conservation effort. Other benefits of a strong conservation effort include less environmental damage, less dependence on foreign oil, and greater flexibility in choosing among energy supply sources. Thus, consideration should be given to new public policy initiatives to promote fuel conservation investments.

A good start in this direction was provided in the Energy Conservation and Production Act of 1976, which authorized two important measures to promote conservation investments: A 3-year, $200 million grant program to assist low-income persons in weatherizing their homes, and a 3-year $2 billion loan guarantee program to encourage conservation-related investments in public and commercial buildings. These incentives pale in comparison to the magnitude of conservation investments needed over the next decade, however.

Significant new measures toward these ends would be provided with the Carter administration's proposed national energy plan, [54] which called for the following direct incentives for conservation investments:

Tax credits of 15 to 20 percent to homeowners for investments in approved conservation measures.

The requirement that State public utility commissions direct their regulated utilities to offer residential customers a "turnkey" conservation service, financed by loans repaid through monthly bills.

Amendments to the Federal Home Loan Mortgage Corporation Act, the Federal National Mortgage Association Charter Act, and the National Housing Act to help insure that capital is available to homeowners through private lending institutions at reasonable interest rates for residential conservation investments.

Increased funds ($530 million for 1978–80) to aid people with low incomes in weatherizing their homes.

A tax credit of 10 percent, in addition to the existing 10-percent tax credit to businesses for investments in approved conservation measures.

It may be necessary to go beyond even these proposals and raise new revenues to help finance conservation investments on a larger scale. An energy tax levied for this purpose would help in achieving fuel conservation goals by reducing demand through higher prices as well as by providing revenues for subsidizing conservation investments. A high-priority item for energy policy research should be to explore in depth the merits and implications of alternative proposals for encouraging conservation investments.

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