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Author
Schipper, Lee.

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Energy and Environment Division
Lawrence Berkeley Laboratory
University of California

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TOWARDS MORE PRODUCTIVE ENERGY UTILIZATION

Lee Schipper

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Towards More Productive Energy Utilization

Lee Schipper
Energy & Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California

ABSTRACT

This review discusses the nature of energy use and strategies which increase the efficiency of energy use. Measures of physical and economic efficiency are discussed. It is suggested that specific energy requirements of tasks in the United States could be reduced by 33-40% over the next few decades at cost savings to energy users. Most of the energy conservation strategies required would have only a slight effect on life style, as well.

In addition to saving energy and money, higher energy use efficiency raises the total demand for labor in the economy, lowers pollution, reduces the total capital requirements of future energy activities, and allows society to proceed cautiously with risky or marginal energy sources.

Many barriers to more efficient energy utilization exist, barriers whose solutions are socio-economic or political rather than technical. These barriers are reviewed, and some suggestions are made which would allow society to overcome them in seeking to use energy more efficiently than today.

I. INTRODUCTION

Energy planners in the late 1960s, projecting growth in energy use on the basis of past experience, compared the expected future demand for energy with possible supplies and generally concluded that a gap (Figure 1) would appear between demand and supply from domestic energy sources. It was suggested that the gap be filled by a variety of solutions: expanded oil imports; accelerated use of nuclear power or coal; enhanced harvesting of domestic oil and gas; or development of synthetic fuels, solar energy, geothermal energy, or some other new form of fuel, heat, or work.[1] Today all of these supply options are still potentially important, but they are far more expensive than the oil, gas, and electricity that were available in the late 1960s. This suggests that a more productive use of energy can more economically supply much of the well-being that otherwise would be made available by using more energy. This higher efficiency, or higher productivity, of energy use is called energy conservation.

Until recently conservation was virtually ignored or dismissed in work dealing with energy (2, 3). A typical view was expressed in the prognosis of the Chase Manhattan Bank (5, p. 52), which asserted that

> analysis of the uses of energy reveals little scope for major living. The great bulk of the energy is utilized for essential purposes—as much as two thirds is for business related reasons. And most of the remaining third serves essential private needs. Conceivably, the use of energy for such recreational purposes as vacation travel and the viewing of television might be reduced—but not without widespread economic and political repercussions. There are some minor uses of energy that could be regarded as strictly non-essential—but their elimination would not permit any significant saving.

More informed studies of energy use contradict this analysis. Especially misleading is the subjective phrase "essential purposes," which obscures the whole question of efficiency. Careful analysis of energy use has revealed an enormous potential for energy conservation (6-15). The most recent forecasts from the Energy Research and Development Administration (ERDA) (16) suggest that US energy needs in the 1990s could be 20-40% below what was previously expected, as higher energy prices and new end-use technologies help Americans squeeze more economic and personal well-being from every Btu. This review deals with some of the implications of more productive energy utilization.

II. THE NATURE OF ENERGY CONSERVATION

Insights From Physical Sciences and Economics

All energy systems and energy use must obey the laws of physics, in particular the laws of thermodynamics (17-19)[2] (see Table 1). "Using" or "consuming" energy really means converting high-quality energy, stored in fuels or as falling water, into heat and work and ultimately into low-quality heat near the temperature of the environment and no longer available to do work. The second law of thermodynamics assures that fuel, the ability to do work, or the quality of energy, is indeed consumed when energy is "used" by society. Ideally economics guides energy consumers (and producers of goods and services) in the choices of how and how well to convert energy use into goods and services or other forms of utility that increase human welfare. It is widely recognized, however, that energy use is a complicated social phenomenon, the full understanding of which demands interdisciplinary analysis far beyond ordinary economics or physical science (20, 21).[3]

Energy is used in the economy, along with other resources, to produce goods, services, transportation, environmental conditions (heating, cooling), or other life-support systems, and conveniences. Economic resources (factors of production) include capital (with design and know-how), labor, land, energy, and the environment, which absorbs pollution. These factors are compared and evaluated for economic decisions by attaching prices, or dollar values, to them, as well as to the output produced by their use. Because energy is but one input to processes, minimizing energy use alone does not always equate with minimizing total costs. What has aroused the scientific community, however, is the fact that careful energy conservation does reduce total costs. This suggests the following definition of energy conservation:

> the strategy of adjusting and optimizing energy-using systems and procedures so as to reduce energy requirements per unit of output (or "well-being") while holding constant or reducing total costs or providing the output from these systems.

Conservation techniques will (*a*) improve the delivery of energy and reduce the specific energy requirements of processes or systems, or (*b*) modify the tasks or goals of energy use. Improving the efficiency of air conditioners reduces the energy required to pump each unit of heat out of a room, while redesigning the house can reduce the amount of heat that needs to be pumped out in the first place. From an economic point of view, conservation strategies substitute other economic resources for energy. The most important of these is capital. Conservation can be viewed as an investment, with certain rate of return.

Conserving has always been identified by economists as the practice of saving something that might be more valuable in the future (22, 23). Furthermore, conservation as increased efficiency allows energy to be saved at no sacrifice in the goals of energy use. Since most consumers have a definite time preference toward the present, few will automatically save for the future without rewards. The rewards for conserving energy are the economic savings that conservation strategies yield.

There are other rewards for conserving energy not measured by direct monetary savings. Some benefits are difficult to perceive by the saver as, for example, lower future prices for fuels in the United States and abroad, fuels saved for use by future generations, lessened dependence on foreign sources of fuel, lessened environmental burdens, and other "hidden benefits" (14). I believe, however, that the largest stimulus to a more efficient energy utilization will occur in response to direct economic incentives and governmental policies designed to aid those incentives.

Some discussions of conservation implicity or explicity equate conservation with sacrifice of desired life-styles, acceptance of lower standards of living, or denial of economic opportunity to low-income groups (24, 25).[4] It will be argued here repeatedly that the strategies that bring about the largest savings in energy use need have few or none of the above effects. The difference between shortages, either short-term or long-term, and true reduction of specific energy needs brought about by more effective utilization must be borne in mind when energy policies are discussed.

Energy Use and Standard of Living

For many years it has been common practice to investigate the relation between energy use and gross national product (GNP) (26), often referred to as affluence or standard of living (Figure 2). Such relationships help to distinguish between wealthy and underdeveloped countries. Historical data also show correlations between the rise in GNP and the

rise in energy use in a single country (27, 28) (Figure 3).

These analyses, however, ignore many important factors that influence actual energy use and the well-being derived therefrom, such as

1. geographic, demographic, and meteorological differences among countries or regions;
2. cultural differences among peoples: advertising, personal habits, and values;
3. differences in economic conditions, including energy prices; the breakdown of inputs and outputs in the GNP; the pace of economic growth; and pollution;
4. physical differences in the structure of the GNP, as well as in the technical efficiency of energy use.

The present scatter of countries with high GNP and varied rates of energy use (Figure 2) suggests that the energy-GNP relationship is much more flexible than previously thought,[5] the level of GNP no longer dictating energy requirements of the economy. Additionally it has been suggested that the rate of growth in the GNP can be uncoupled from the rate of growth in energy use, especially as energy costs rise (29).

Careful comparisons among countries (30-34) often reveal energy conservation strategies and allow the side effects of these strategies to be examined at the same time. In Sweden, for example, a significant fraction of all energy consumed in thermal power plants is utilized as low-temperature process or space heating, as the details of Figure 4 illustrate. An evaluation taking into account the slightly smaller size of Swedish dwellings (compared with the United States), the higher percentage of apartments, the higher efficiencies of the well-maintained apartment heating systems in Sweden, and the Swedish climate shows that space heating requirements in Sweden are 30-40% lower per square meter of space in homes (and commercial buildings) than in the United States. Since indoor temperatures in Sweden are in the range of 23-24°C (73-75°F), the differences must be ascribed to generally more energy-efficient structures in Sweden (33, 35).

In the transportation sector Swedish automobiles are considerably lighter than those in the United States, averaging around 1100 kg.

A larger fraction of short intra-city trips in Sweden are made via mass transit. More passenger trips in Sweden are made by train, with higher load factors, than in the United States, or by chartered jet, again with higher load factors than commercial aviation in the United States. Swedes travel nearly as much as Americans but with far less energy (33, 35).

In the industrial sector Sweden also uses less energy for each ton of steel, paper, cement, and most other industrial products, including allowance for the difference in heat rates. Sweden's import/export statistics indicate that 9-10% of all energy consumed in Sweden is embodied in exported products, while imports of refined petroleum products embody about 5% of Sweden's total energy consumption, this energy being consumed by refineries outside Sweden (33, 35, 36).

On balance Sweden requires about half as much energy per dollar of GNP as the United States. Some of this is certainly due to the large share of hydropower in the Swedish energy economy and the larger fraction of Sweden's GNP that goes to services, particularly social welfare. But most of the difference arises out of the strikingly more efficient ways in which Swedes convert fuel into comfort, transportation, and industrial output. Similar conclusions were reached in a study of West Germany (32).

Energy use per dollar of GNP has changed with time in the United States, reflecting changes in the goals of energy use as well as in efficiencies. And there are variations from place to place within the United States today in the amount of insulation in buildings (6, 9, 13), the use of public transportation (37-39), weight and other factors in automobiles, and the prices of fuels and electricity (40, 41). The differences in energy consumed for heating can be striking. Table 2 gives natural gas consumption per degree day for the largest US metropolitan areas. The variation is enormous; in the warm cities, or where natural gas is relatively inexpensive, builders and homeowners understandably ignore energy in designing and living in homes, since total heating costs are low.

It is clear from the foregoing discussion that energy use alone is an insufficient measure of how well people live. Variations in energy use and efficiency among different countries, different regions of the same country, or during different time periods in the same country or region indicate that the energy requirements of tasks vary considerably.

High rates of energy use per dollar of GNP may indicate inefficient use of energy as well as high standard of living. Understanding the efficiency of energy use will allow us to see how much more well-being can be generated from each unit of energy used.

Efficiency of Energy Utilization

Physical Efficiency Physical measures of efficiency are 17,000 important indicators of the potential for conservation. Traditionally the first law of thermodynamics (see Table 1) has been used to express efficiency as

$$\frac{\text{(energy provided or transferred in desired form and place)}}{\text{(energy input to system)}}$$

First-law efficiencies follow the flow of work and heat in systems, accounting for all uses and losses at the boundaries in and out of the system. Figure 5 shows first-law efficiencies for air conditioners (43). Motors (44) and other devices (45) have been carefully studied. First-law efficiencies are numerically less than one, except in the case of refrigerators, air conditioners, or heat pumps, where the amount of heat moved is usually greater than the amount of work (usually electricity) consumed. The "spaghetti bowl" chart, drawn first by Cook (Figure 6), shows an approximate first-law accounting of US energy use in 1971 [see also (45) and for other "bowls" from a variety of years see (46)].

It is important to note, however, that first-law efficiencies can be misleading. As suggested by the study done by the American Physical Society (45), the second law of thermodynamics gives a more relevant measure of physical efficiency in cases where temperature changes are involved, by comparing the energy (as work or heat) theoretically required to perform a task with that actually used. Note that 60% of all fuel is consumed in order to change the temperature of environments or substances and that 85% of electricity and nearly all of transportation is provided by heat engines. Second-law efficiency is measured by

$$\frac{\text{(theoretical minimum energy required by second law)}}{\text{(energy actually consumed)}}$$

Theoretical energy requirements of tasks are based on properties of materials, environments, and heat engines that convert heat to work and vice versa. The amount of work needed to pump heat across the small temperature differences common to most household or building situations and industrial tasks is small compared with the amount of work that could be extracted from combustion of the fuels that are used in these applications—hence the low efficiencies in Table 3. By contrast, modern power plants or industries using high-temperature heat utilize a larger fraction of the ability to do work that is stored in fuel. An ever greater efficiency can be obtained by modification of industrial procedures to allow use of the exhaust heat from these high-temperature processes in other applications, including generation of electricity (47). Locating power plants near communities permits utilization of power plant waste heat (via cooling water) for district heating, as is done in Sweden (33). Putting small power plants in factories allows economic cogeneration of both heat and electricity in a mix optimized for the temperature and horsepower requirements of the factory (47).

Some processes are best understood by examining both first- and second-law efficiency. Improving heat-transfer properties from flame to boiler in a power plant, which is a first-law procedure, also increases temperature differences that the plant utilizes and therefore improves second-law efficiency (45). Often, too, redefinition of the tasks involved in energy use allows a higher physical efficiency. Use of recycled scrap lowers process heat and electricity requirements for most metals. Heat pumps might utilize groundwater, the temperature of which varies little during the year, instead of outdoor air, as a heat source for space heating. The temperature differences between the source and the indoor space is then reduced, so less work is required (45). While physical analysis of efficiency gives an important measure of possibilities for energy conservation, the tasks in question should also be evaluated.

Design and Maintenance Efficiency Sometimes it is useful to measure efficiency by relating the energy requirements of a task to the physical or economic output of that task. Design intensity is expressed this way, employing units such as Btu/passenger mile (for passenger transportation, see Figure 7), Btu/degree day (for space heating), or Btu/ton (for industrial output). Design efficiencies are the inverse of these intensities. But whether a task is carried out at its rated design efficiency usually depends on how well the system or process is maintained. Maintenance efficiency compares rated design

efficiency with operating design efficiency. The design efficiency may also depend on other factors; the seasonal dependence of the design efficiency of space heating systems (48) is a good example.

Some systems, such as mass transit and automobiles, are designed to provide far more output (passenger miles) per unit of energy consumed than is usually used (Figure 7). Uninsulated, poorly designed structures require more energy than insulated, carefully built ones (a design efficiency), and poorly maintained heating systems deliver less comfort, per unit of energy used, than well-maintained systems (a maintenance efficiency). By modifying systems, energy conservation procedures improve design efficiency, even before physical efficiencies are changed.

Economic Efficiency Economic efficiency is measured by comparing the total cost of using energy in various systems at various levels of physical efficiency. "Cost" is usually, but not always, measured as the total direct cost of providing useful output or services from energy, measured over the lifetime of the system. Cost includes purchase price, interest or opportunity cost on the investment involved, taxes, and maintenance costs (49).[6] Thus economic efficiency considers both the cost of the energy and the cost of the energy system. Ideally, although rarely in practice, economic efficiency includes environmental or other external costs associated with energy systems (22, 23), as well as the cost of the risk of the fuel or system being unavailable in the future and the prospects for changes in fuel costs. That system which provides the desired output for the lowest cost is the most efficient. Unless otherwise indicated, this review uses the economic definition of efficiency in terms of life-cycle direct costs, although compelling reasons have been suggested (22, 23) for including environmental costs and other non-market costs or exigencies such as the reduction of oil imports or threats to national security.

Economic efficiency can also be identified with total resource productivity. For many years economists usually concentrated their studies on labor productivity, since resource costs were stable. Now, however, energy costs have risen faster than labor costs, and in some cases energy, rather than labor unions, has gone on strike, as in the case of the 1973-1974 oil embargo. If energy prices continue to lead all other factors in inflation, including wages, then it can be expected that energy users will accelerate efforts to increase the economic and physical efficiency of energy use. Part of the reason for the relatively high efficiency of energy use in Sweden can probably be ascribed to the high cost of energy there. It has been noted, however, that over the past 25 years the physical and economic efficiency of energy use in US industry has increased in spite of falling real energy prices (29). In this sense energy conservation leads to a more productive use of resources.

Physical or monetary values are not always sufficient for analyzing energy use because people often make decisions on the basis of variables such as exertion, luxury, convenience, time, risk, pleasure, or nuisance. Urban design, employment, and life-style are other social aspects of energy use that influence energy choices. For example, I use taxis when I am in Washington DC (but rarely elsewhere) because the value of time there is usually worth the expense of taxis and the loss of exercise. Important values like these must enter into energy planning and considerations of conservation strategies. The object of conservation is not to deny ourselves conveniences, preferences, necessities, or other aspects of life-styles, but instead to make these activities more economically efficient. The next sections discuss how this might come about through energy conservation.

ENERGY USE AND CONSERVATION

Kinds of Energy Use

One way to display kinds of energy use is the traditional breakdown of energy use by economic sector and task shown in Figure 8, which can be compared to Figure 6, in which the flow of fuels from source to economic sector was illustrated. Another possible description of energy use is by task and quality, as the American Physical Society study (45) suggested (Table 3).

Often it is desirable to learn the energy requirements of individual economic or physical activities. Energy analysis allows these requirements to be evaluated through accounts of purchases of energy by firms, by using input-output techniques, (50-52) or measurement of fuel consumption in production processes (53-55) (Table 4). Energy-intensive activities are those for which the specific energy requirements per unit of physical or economic output are significantly higher than for the economy as a whole. Energy analysis also shows how much energy must be consumed to build and run energy production

technologies (Table 5). Such analysis is particularly important for nuclear power programs or advanced fossil fuel conversion schemes (56-60).[7] Energy analysis provides a reminder that investing dollars in almost everything requires investing energy.

Energy analysis can also be used to predict the energy cost of implementing conservation strategies, but consideration of the economics involved suggests that the periods for energy payoff will be short (61). Let us examine why this is so. Expenditures for energy require between 2×10^5 and 10×10^5 Btu per dollar. The same dollars spent on conservation investments or other non-energy purchases require only about 6-8 $\times 10^4$ Btu per dollar (50-52). Even if the present value of the energy saved from a strategy is somewhat less than the cost of the strategy, energy will be saved. However, in the case of energy technologies that are materials-intensive, such as solar photovoltaic and central-station solar power plants, large energy investments may be required, and these should be carefully evaluated.

These objective descriptions about energy use and cost avoid important judgements about the tasks involved. Must cars weigh 6000 lbs? Must a refrigerator be so poorly insulated as to "require" an electric resistance heater in its skin to drive off condensation? Questions like these suggest that while physical science and economics answer many of the technical questions about efficiencies of energy use alternatives, political and sociological analysis is required to explain why energy use patterns have developed (20, 21). Understanding the quantitative aspects of energy use is, however, essential in order to be able to evaluate energy conservation strategies. These strategies are discussed next.

Conservation Strategies and Their Applications

In Table 6 a classification of conservation strategies is suggested. The most important stragegies for existing systems are leak plugging, management, and mode mixing, and for future systems, input juggling, thrifty technology, and output juggling. If strategies like these are applied to important end uses of energy, savings of 10-50% of specific energy requirements result (Table 7). Applying all of these savings to the 1975 US energy economy would have the effect of reducing total energy consumption by approximately 33%, as is illustrated in Figure 9 (6-13, 45, 62). Since these savings require months to decades to be achieved, they appear as slower growth in energy use. This scenario is often referred to as the "technical fix" (see 13). Listed in order of the amount of energy saved, the three most important energy conservation applications are (*a*) better heating and cooling of buildings, (*b*) use of second law as a guide in industrial heat treatment, and (*c*) reduction of the weight of automobiles. The order of implementation time is probably the reverse.

Most of the potential for energy saving in homes and buildings comes from leak plugging and input juggling, as owners or builders invest in technology and design options (listed in Table 7) that lower the requirements for energy. Energy savings from management of systems also can be considerable, as Figure 10 demonstrates for thermostats [(97); for results of leak plugging and management, see (98)]. With new homes, input juggling can reduce energy consumption further with little or no change in the home environment (74, 75, 99), (Figure 11). The savings become larger as higher fuel prices justify increased use of insulation and other techniques that reduce heat loss. This illustrates well the degree to which input juggling might take place in construction of new systems.

Experiments with thrifty technology indicate, however, that even greater residential energy savings can be effected when the total home environment is considered. The Pennsylvania Power and Light Company's experimental low-energy house, shown schematically in Figure 12, would reduce energy use by as much as two thirds compared with ordinary homes, by using solar collectors, heat pumps, heat recovery schemes, and conveniences such as automatic devices that close curtains at sunset to minimize heat losses through windows at night.[8] Other studies of actual and proposed buildings indicate that energy requirements in existing structures can be reduced by 20% in the short run and more over longer periods (76-78, 98), and consumption in new buildings can be reduced by nearly 50%, or more if solar technology is used[9] (78, 81, 82). Figure 13 illustrates the savings achieved in a new office building in Manchester, New Hampshire by combining most of the conservation strategies discussed here.

In transportation, improvements in the physical efficiency of engines, such as greater use of diesel motors or development of advanced propulsion systems in cars (thrifty technology), would save a good deal

of energy[10], but reducing the weight of cars (output juggling) would save even more (45, 94) (Figure 14). However, the degree to which people might reduce travel (output juggling) is difficult to estimate. Mode mixing depends on the availability and cost of alternative forms of passenger and freight transport, although increased load factors in public transit, including air transport, would save energy (38, 100). Improved freight handling procedures (management), including permission for interstate trucks to be fully loaded on return trips, would greatly increase energy efficiency in the movement of goods (6, 91).

Many of the savings in transportation are not dependent on technological or economic breakthroughs but instead await changes in socioeconomic patterns, habits, and laws. Trends can work in the wrong direction also; both a continuation of population dispersal into suburbia and exurbia[11] (101) and the development of complicated or extremely fast vehicles, such as SST's, high-speed rail vehicles, or short-takeoff and short-landing aircraft, could increase the energy requirements per passenger-mile and per capita miles of transportation. These trends are examples of how output juggling increases energy use.

In energy-intensive industries, engineers and computers have been employed to effect immediate savings of 10-20% through leak plugging (6, 12, 68, 83-86). Table 8 shows some of the results of the energy conservation programs of E. I. Dupont Company (83). The costs of the Dupont program and the actual equipment adjustments required were far less than the savings in fuel expenditures. Similar programs have been developed by I.B.M., Honeywell Corporation, and Johnson Controls.

In the longer run, greater energy savings in industry are realizable as input juggling and thrifty technology help reduce process energy requirements of materials closer to thermodynamic minima (45, 86; see also article by C. A. Berg in this volume) or as tasks are modified, especially to allow utilization of waste heat (45, 62). The economically optimum level of energy use will be sensitive to the price of fuel (86), but most process energy requirements declined during the past 25 years even as fuel prices fell (29).

Figure 15 shows this decline in energy consumed for an important energy-intensive product, cement (102). Input juggling has allowed each of the two processes to become more efficient, and at the same time the manufacturers have shifted to the more efficient dry process for future production. Similar short- and long-term trends have been observed in nearly every energy-intensive industry in the United States (103) and also in Sweden, where process energy requirements are generally lower (33).

The discussion of energy conservation strategies and their applications illustrates the different kinds of approaches to conservation that energy users can employ. Certainly research and development of techniques that promise even greater energy savings will play an important role in increasing the overall impact and pace of conservation. Understanding the barriers to more efficient energy use (see below) will also aid society and individuals in implementation of conservation options. But the economics of conservation will doubtless determine how fast new technologies will be adopted and how well society will work to circumvent difficulties in implementing them. Some aspects of economics are discussed in the next section.

Economics of Conservation

Economic efficiency is, in theory, the basis for decisions made by energy consumers. Economics determines how many extra dollars can be spent on improving the heat-transfer properties of an air conditioner, how much extra investment might be justified in choosing a diesel engine over a conventional one in an auto, or how much insulation should be added to a structure. All of these decisions affect physical efficiencies. In theory an informed energy consumer will invest in higher physical efficiency as long as the next increment of investment is less than the present value of extra energy saved [see especially (49)].

Most of the conservation options cited in Table 7 have been analyzed with respect to first cost, interest and taxes, and so forth. Fortunately the strategies that raise the physical efficiencies of energy systems raise the economic efficiencies as well. Some energy conservation strategies, such as insulation in refrigerators and water heaters, pay back the initial incremental investments in months (69-71), while others, such as industrial techniques, building insulation, and more efficient heating/cooling systems, require longer periods. Some options save money from the beginning, such as smaller cars and innovative designs of structures, while others, such as mass transit systems, are difficult to evaluate because much of the payoff accrues to society in general.

A few examples are worth noting here. Moyers (43) showed how much money a consumer could economically invest in a more efficient room air conditioner, based on the first-law efficiencies of models shown in Figure 5. His results (Figure 16) depend on number of hours of use per year, price of electricity, cost of money, and inside temperature desired. The calculations of Berg (68) (Table 9) compare yearly operating costs of different air conditioners and show clearly the savings achieved by higher efficiency. As Ross & Williams noted (62), it is usually less expensive for the user to invest in higher efficiency than for the local electricity utility to invest in extra peak capacity.

Other calculations show that proper insulation in buildings saves 20-50% of total energy and 10-30% of the expense required for heating or cooling (63) and that heat pumps save at least 30% of total energy and 20-30% of the total costs of using electric resistance heat (45, 62, 64, 104, 105). The alternative of providing extra energy by building more oil refineries, pipelines, and power plants would be far more expensive both in initial investment and in life-cycle costs (62).

It is also important to consider the economic and energy impact of input juggling applied to all energy-using systems in a single structure. For example, Dubin et al evaluated a large number of energy conservation options that apply to electric homes in Florida (74). These are listed in Table 10, along with expected savings from each technology in kilowatt-hours per year consumed in the home (74). The incremental capital costs of each option can be compared with the present value of the electricity saved over the lifetime of the option. For a 30-year payoff time on these houses (15-year payoff time on appliances) the homeowner could invest at least 75¢ (38¢ on appliances) on conservation measures per kilowatt-hour saved yearly, assuming a present cost of 2.5¢/kW-hr and inflation in real cost at or greater than the general rate of interest. In these houses the cost of adding an overhang is not justified by energy savings alone. Solar heating is also difficult to justify on economic grounds because heating requirements in Florida are low, but a combined water heating/air space conditioning system might be economically feasible.

The kinds of analyses reviewed here for buildings have been performed on many other aspects of energy use (6, 68, 86). Such evaluations of the economic and energy savings potentials of conservation strategies allow planners to project future energy needs based on the economically optimal needs for energy. This is explored in the next section.

Conservation and The Energy Future

It has been emphasized in this review that the tasks for which energy is consumed can be carried out in different ways that require widely varying amounts of energy. Figure 17 illustrates a general relationship between economic efficiency (104) and design efficiency. Some combination of energy with other inputs will provide the most economic use of all resources. This is shown symbolically by the optimal zero point at the minimum of the cost-energy curve in Figure 17. Environmental costs tent to push the optimum toward physically more efficient energy use, a fact rarely considered seriously in evaluations of the economics of solar energy or other supply or conservation options (22, 23, 106, 107, chapter by Budnitz and Holdren in this volume; also section on conservation and pollution, below).

That the energy use in most systems in 1970 or 1975 was economically inefficient is indicated by the position in Figure 18 of actual for those years. Here projected gives an estimate of the energy use that would occur if energy consumption grew at historical growth rates in spite of price increases. If energy costs continue to rise, however, then the economically optimal amount of specific energy consumption for tasks will fall, as is indicated by 0_{90} in Figure 18.

The discussion of "barriers" (below) presents reasons why energy use today is not optimal and why certain governmental actions may be necessary if energy use is to approach the optimal point in the future. Energy conservation policy can be considered as that group of laws, standards, incentives, taxes, or other governmental, institutional, or private actions that aid this approach to the optimal energy utilization.

A curve like those in Figure 18 can be drawn for most energy-using activities or systems, as is done for space comfort in buildings in Figure 19. The data presented in Tables 8 or 9 would fit on a curve of this shape. The costs of providing comfort fall with conservation, first through retrofitting of insulation, then through more sophisticated designs and increased efficiency of new structures, as long as marginal benefits exceed costs. Some options, like solar heating and cooling,

may not be the most economic in every case, as is symbolized by the upturn of the cost curve as energy use falls further. As fuel costs rise, however, solar heating and cooling will become economically efficient in more and more instances, in comparison with fueled or electric systems[12] (see also 43, 49, 63).

Amassing a large number of curves such as in Figure 19 is a formidable task if one is to include all of the options available to the major energy-consuming systems in this country. However, such curves would then allow projection of energy needs both on the basis of desired goods and services and on the basis of the most economic, specific energy needs of these goods and services. The cost of conserving an additional Btu for each task, relative to today's consumption, could be compared with the cost of producing each additional Btu beyond some reference price and supply that is assured. Adding up these curves would indicate ranges and costs of total supply and demand. The area where these demand and supply curves cross would indicate the most economic amount of energy consumption in a future year, for a given mix of tasks. Other balances of supply and demand would probably cost more than the optimum. This is indicated in Figure 20. Non-market factors, such as environmental costs or social variables, tend to diffuse the optimal point somewhat, as would differences in judgement and uncertainties about future technologies. If policymakers or their constituents felt that a significant departure from this optimum were either desirable or dangerous, policies could be adopted that would aid or inhibit the economic and technical factors that shape energy use. In California, for example, the Energy Resources Conservation and Development Commission has been empowered to develop such policies.

At the same time, research and development of conservation applications to present and future patterns of energy use can change the shapes of Figures 19 and 20 by making energy use even more economically efficient. For example, improvements in the heat-transfer properties of materials could lower the electricity requirements of heat pumps, and development of new kinds of insulation could lower the cost of insulating structures. Such applications are complementary approaches to the same goal—aiding society in deriving more well-being from energy use.

Recent systematic studies of energy options and policies, such as the Ford Foundation-sponsored Energy Policy Project (13) or ERDA's "Creating Energy Choices for the Future" (16), reflect the kind of economic evaluations suggested here, as well as the prospects for increased energy savings made possible through R & D into energy use and conservation. Energy projections from these studies, which explicitly recognize the effects of more efficient energy use, are summarized in Figures 21 and 22. Although some observers feel that energy demand cannot be modified significantly by technical and economic changes (108, 109), it is clear that an enormous potential exists for raising the efficiency of energy use. It is important, however, to consider the long-term implications of realizing this potential.

III. LONG-TERM IMPLICATIONS OF EFFICIENT ENERGY USE

Total expenses for energy in the United States average around 10% of the GNP (13, 14), and this figure is expected to grow. Therefore, a substantial conservation program means that billions of dollars will be redirected from energy expenditures to non-energy expenditures. Policymakers considering efficiency standards, taxes, restrictions on energy use, or subsidies for energy efficiency will want to know what might happen to the economy when energy is used more efficiently. This discussion explores the effects of conservation on employment, pollution, climate for capital investment, and energy resources.

Employment

The use of energy is essential to nearly all employment in this country, but energy requirements of different goods and services vary greatly. Input-output techniques reveal the average amounts of energy and labor required to satisfy the demand for a product or service (50-52). These values include indirect energy and labor required by industries whose output was used by the producing industries and the energy and labor required by suppliers of those industries, and so on.

Figure 23 displays the energy and labor requirements per dollar of demand for some goods and services, and Table 11 gives the intensities of some important personal consumption activities. Energy forms (and raw materials) have low labor intensity and high energy intensity. Manufacturing is intermediate, whereas services are labor-intensive but not energy-intensive. Closer inspection of the energy industries shows them to be very capital-intensive but far less labor-

intensive than the economy as a whole [see Tables 3 and 4 in (14)].

The strategies of energy conservation considered here substitute capital, materials, labor, know-how, or management for energy. Compare, for example, two air conditioners of equal capacity, operating in similar homes under similar loads in the same climatic region, one requiring half the power of the other. If a consumer buys the more efficient unit, some of the money otherwise spent on energy is used for extra materials and labor, and this expenditure results in a more carefully constructed, more efficient air conditioner. Since manufacturing is generally more labor-intensive than electric utilities, the redirection of spending—from paying for electricity to investment in a more efficient unit—raises the total demand for labor per unit of air conditioner and still provides for the consumer's desire for comfort [see Table 11, or details in (50)]. When the consumer spends the money he saved by energy conservation, his new purchases will require increased labor, in contrast to buying electricity (50-52). The result is more goods or services and more employment, with less energy used. The notion that welfare or employment can only grow in step with energy use completely ignores the effects of strategies that increase efficiency.

In industries that conserve energy, employment will generally increase, since nearly every energy conservation strategy calls for energy specialists to monitor and adjust energy usage in the plant or building. Similarly, the implementation of long-range conservation plans (input juggling, thrifty technology) calls for equipment, consultants, architects and designers, and other specialists not otherwise required. The costs of changing to a more efficient use of energy are, of course, borne out of savings from energy bills, and the net dollar savings is either passed on to consumers, reinvested, or taken out in profits. In these and most other conservation applications, energy expenditures are replaced by non-energy expenditures, which generally increase employment.

One of the arguments for output juggling has been the observation that goods and services that are less energy-intensive tend to be labor-intensive (Table 11). If consumers preferred less energy-intensive items, whether in response to higher energy prices or from a pro bono desire to save energy [as suggested in (95) concerning gifts], the energy/GNP ratio could decrease even with no changes in the technologies of energy utilization in production of goods or in the ratio of services to goods. Some changes in consumer preferences, such as greater use of buses, could improve design efficiency by increasing load factors (100); changes in travel and tourism would effect transportation energy use; and changes in aesthetic and architectural preferences would alter energy demands in housing and buildings (110).

Hannon (50) concluded that output juggling cannot save a large percentage of US energy use. On the other hand, a study of Sweden (33) suggests that substitution of social services for large cars or other energy-intensive personal consumption does reduce energy consumption somewhat for a given level of GNP. But it may not be necessary to engage in output juggling to save energy, since the other techniques discussed here promise such large savings with little or no change either in lifestyle or in the mix of goods and services in final demand.

It is important to remember that many of the changing patterns of employment and intermediate demands effected by a policy of energy conservation would appear in any case as a result of natural market forces, although perhaps over a longer period of time. Certainly any changes in the structure of the economy, whether gradual or forced by an embargo, could create temporary unemployment and some social dislocation. The short-term effects of changing energy-use patterns will continue to raise issues, and one must insist that those affected not be asked to bear a burden that is too heavy. Society can and must cushion these effects during the transition to a period of more efficient energy utilization.

Conservation and Pollution

When energy-conserving practices are adopted, the net result is an increase of useful output per unit of energy input. This has important environmental consequences because energy use and harvesting are among the most polluting activities in our economy. If a homeowner in the Tennessee Valley Authority service area replaces electric resistance heating with a heat pump (saving approximately 50% of the electricity commonly used to heat homes there), less coal need be mined [about 3-4 tons less per house per year (105)], fewer power plants need be built, less cooling water is used, and less air, land, and water pollution occurs for each night of comfort in the winter or day of cooling in the

summer. Similar considerations apply to industries that conserve energy. Since the demands for materials required by energy-saving technologies are usually only slightly higher than correspondingly less efficient options, the reduction in all forms of pollution will be appreciable.

The effect of conservation on pollution is important, for as the number of various polluters grows and as the amount of pollutants grows in kind and total amout, more abatement technology will be required to hold constant the concentration of pollutants in the environment (107). But costs of pollution control tend to increase faster than the increments of control (Figure 24). The total bill for abatement of pollution control could thus rise in the future faster than the GNP itself (106, 111). Polution also means costs to health, welfare, and property (112-114). More efficient energy use reduces all of these costs and the pollution as well.

It is often said that large amounts of energy will be needed to clean up the environment (115). Actually the energy requirements in environmental control, while not insignificant, are not large. It has been estimated that energy requirements for pollution control raise total energy consumption by only 2-4% (116, 117). Reduced automobile size, increased use of mass transit, or longer-lived cars all reduce pollution per passenger mile, as well as provide energy savings. In addition the percentage of fuel penalty imposed by pollution control on automobile emissions is generally smaller for lighter cars than for heavier ones (94, 116). Moreover, recycling, which reduces solid wastes, also saves energy (87-89, 119), and some solid waste can even be used as fuel.

Use of energy has two effects on well-being—it is positive through its application to satisfying human needs and negative through its adverse effects on the environment (see Figure 25). Increased economic and human well-being obtained per unit of energy, through conservation, reduces the environmental costs per unit of well-being, and this adds to our welfare.

Energy Conservation and Investment Requirements

New energy production facilities demand large, and ever increasing, amounts of capital per Btu produced or per unit of capacity. The energy sources most often cited as vital to our energy future—nuclear energy, shale oil, coal gasification, enhanced recovery of oil and natural gas—would, if the historical trend continued, require capital investiments over the next 25 years totaling trillions of dollars (118-120), making the energy industry's share of all investment grow faster than the economy as a whole. This means that consumers, industry, and the government would have to forego both consumption and investment, through higher interest rates, higher prices, or higher taxes, in order to finance the expansion of the energy industry.

Higher energy productivity, on the other hand, slows the growth of investment in energy systems to a more manageable rate, easing pressure on interest rates and allowing more personal consumption of other investments, because conservation is cheaper. If the criterion of greatest marginal benefit is applied to investments, it can be shown that proper conservation techniques (see Table 7) save more energy than new energy sources can produce, per dollar invested (62). Some of the money that would have been invested in greater energy production should be invested instead in greater energy productivity—that is, in conservation practices. This point, that conservation is a cheaper substitute for greater production (at least up to the point shown in Figure 20), is not sufficiently appreciated.

The cost of an investment in Btu, or capacity added, is especially important in the case of buildings, which tend to outlast most energy production facilities. The American Institute of Architects (121, 122) estimates that investments in extra efficiency in new and old buildings could economically replace the supply equivalent of 12 million barrels of oil per day by 1990 (Figure 26). Again, a Btu saved costs less than a Btu harvested.

Similar estimates have been made regarding industry. A recent study by Dow Chemical Company (47) estimated that if both electricity and heat were cogenerated on site by large industrial power users, with power and steam being shared with existing public utilities, the required investment of $13 billion would replace an investment in utilities alone of $29 billion and would save the equivalent of 725,000 bbl/day of oil or equivalent. In the Technical Fix scenarios of the Ford Foundation's energy study, a reduction of energy demand by 33% in the year 2000, compared with historical growth, would mean a capital savings of $300 billion (13).

Growth in energy demand would have to be met by construction of energy systems not yet in existence. One can therefore estimate the energy-harvesting facilities that would not be needed if future energy-use technologies become more efficient. Electric resistance heating and large, inefficiently designed office buildings would have been major ingredients in the growth in electricity use. Poorly insulated homes, leaky industrial processes, and fuel-hungry autos make up much of the future demand for fuels based on historical growth [see (5) for a naive description of future demand]. An insulation program alone that would result in a savings of one third of the energy used to heat homes and buildings (more in new structures, and less in existing ones) would replace the equivalent energy output of oil refineries totaling 2 million bbl/day or 75 1,000-MW nuclear power plants operating at 60% capacity factor.[13] Replacing resistance heating with heat pumps would reduce system capacity needs still further (64, 104, 105).

Therefore, what conservation means to investors is that relatively more energy-related investment should take place at the endpoint of energy use, displacing even more dollars on the energy production side. Since the ingredients in more efficient structures and industrial processes are usually highly dependent on careful engineering, quality work, and tender loving care, one expects that the employment requirements of conservation investments will be slightly higher than those for the additional investment in energy production. This point has already been made in the discussion of employment.

Conservation and Marginal Energy Sources

Conservation has another effect on the future of energy production, by slowing the rise in physical and dollar costs associated with marginal, less accessible, more energy-costly sources of energy. "Scarcity" of an energy resource really means "high entropy" (high degree of dispersal) of the energy fuel; increased amounts of high-quality, low-entropy energy fuels are needed to recover each Btu of marginal fuels.

The degree to which the real marginal cost of energy production from conventional sources is rising today is evident from Figure 27 (21). The rise in cost of drilling is nearly exponential with depth. Increased requirements for earth moving, drilling, and water and waste disposal forewarn of rising environmental spoilage per unit of net energy actually gained from all energy harvesting. Lignite, with only half the Btu content of bituminous coal, requires substantially larger environmental disruption per Btu recovered and produces more ash and sulfur per Btu of heat obtained in a boiler (58). A nuclear power program can consume a large fraction of its own output during excessively rapid expansion (59, 60), and tertiary oil recovery, shale oil, and coal gasification produce far less net energy than the actual Btu content of the fuel resource in situ (21). Vyas & Bodle (123) have estimated the net energy output from various synthetic fuel processes (Table 12).

Expensive or marginal energy resources, no matter how large they may be in Btu content, pose tremendous environmental problems if they are to be exploited on a large scale compared with 1975 energy demands in the United States (106).[14] Environmental questions are also important for the technology of nuclear power where the risks from mismanagement are great (124). Conservation, in promoting slower growth in energy harvesting, allows society to buy time for the testing and environmental engineering that are required to insure safe and clean recovery of net energy and other social benefits from these resources. "Income" sources such as solar or geothermal energy, which are large in supply but limited in utilization rate, are better suited to an energy budget reduced by conservation. Solar energy, in particular, offers environmental advantages because it makes use of already existing solar heat (125). A society's choices of which energy sources it will exploit depend greatly on what total rate of energy utilization will be required. Conservation makes that rate more manageable.

Social considerations related to future energy sources are also important. Certainly the cost to society of energy shortages is large. But there will be many social costs of the new energy sources, which are far more complex technologically and environmentally than energy conservation strategies. We must consider fully the social costs of building the Alaska pipeline, of offshore oil development with its hazard of oil spills, of creating and maintaining large-scale strip mining, shale oil, or coal gasification centers in the West. Distressing is the lack of understanding about the social implications of a large-scale commitment to nuclear power, including the social cost of the eternal vigilance that proponents and critics of nuclear power agree is required in order to manage the nuclear waste products, which long outlast the power plants themselves (124, 126, 127). These kinds of social issues must influence

decision-making about energy use, especially since they favor more efficient energy use than would be dictated solely by microeconomic considerations.[15]

IV. NONTECHNICAL BARRIERS TO EFFICIENT ENERGY UTILIZATION

Studies of insulation (63) and air conditioners (43) suggested that even before energy prices began to rise in the early 1970's energy use for space comfort was far from optimal. This section reviews some of the reasons why energy use in these and other applications today may not be economically efficient. These reasons suggest that important barriers to more efficient energy use in the future still exist.

Economists invoke the mechanism of the marketplace as the measure of efficient use of resources. Price determines the optimal use of resources, balancing the rate of supply of energy with the rate of demand. When the price of a commodity rises, the user may elect to use less of that commodity, substitute, or do without the benefits of that commodity. If use is sensitive to price, the relationship between use and price is termed elastic. If, on the other hand, changes in prices do not induce changes in use, or induce relatively small changes in use compared with the change in price, the relationship is termed inelastic [for studies in elasticity of energy use, see (128-130)].

Elasticity is really a characteristic of human behavior, and economic models that predict this behavior are important. Some predictions are illustrated in Figure 28. But responses to higher prices are slow to come about: obsolete systems must be replaced, new technologies must be developed, or the fact must be "discovered" that energy is being wasted. That short-run elasticities to energy prices may be low should not discourage society from expecting that long-run changes in the patterns of energy use will in fact come about as a result of higher prices.

Unfortunately, few studies of elasticity evaluate the efficiency of energy use or model the technical options available to the consumer of energy. Physical analysis of changing economic conditions as well as the technologies involved reveals surprisingly effective options for energy conservation that are not predicted by conventional econometric studies. The summed demand in Figure 28, or the projections of Makhijani and Lichtenberg (72), illustrated in Figure 29, show the often dramatic difference between efficient scenarios and pure exponential growth.

Energy Prices

As was suggested above, the price of various fuels plays a decisive role in determining which of the energy-use options is the most economically efficient. For many years, however, the real prices of energy fuels and electricity fell (13, 41), stimulating growth in energy demand while inhibiting concern for efficiency. Since 1970, however, energy prices have begun to rise dramatically, so it can be expected that the rate of growth of energy use, as well as energy-use patterns, will begin to change in response to changing energy prices. The response can lead to increased efficiency of energy use through application of the first five conservation strategies listed in Table 6 or through output juggling, as energy users turn to products, services, or materials less affected by rising energy costs. Additionally some output juggling may be expected in the form of reduced automobile travel, lower thermostat settings in winter, reduction in hot water use and its temperature, and so on.

There are, however, also distortions and imperfections in energy prices themselves. While the fuel and capital costs of electric utilities are rising, electric power is still sold on a declining block basis in most parts of the country: the more one uses, the less one pays per kilowatt-hour (131-133). As long as large amounts of electric power were cheap, the aluminum smelters ignored efficiency. Similarly, the attractive prospects for large savings in fuel from on-site co-generation of process steam and electricity are severely inhibited by the present rate structure for electricity (47). Extra charges for peak-period usage, when production is most expensive, do not yet exist in the United States, although the maintenance of a peak reserve is expensive in terms of capital, and the peaking equipment is usually less efficient than the baseload equipment (62). It now appears that there will be revisions in electricity pricing schedules in the near future (see the chapter by Sanders in this volume).

Other price distortions are equally harmful. Price controls keep energy prices below market prices and sometimes below actual marginal costs. The depletion allowance on fuels allows some of the "risk" cost of exploration to be paid by taxpayers instead of the fuel users, by allowing producers a substantial tax benefit; other pricing practices for petroleum do the same (134). Elsewhere governmental policy subsidizes housing, highways, or air travel, regulates natural

gas in interstate commerce but not in the state produced, and so on. The result is, of course, a price system wildly distorted from real costs. Economists have long warned that this leads to misallocation of scarce resources.

Further distortions in the price system are caused by the exclusion of environmental costs from market prices. Political battles take place in the US Congress over such environmental issues as a sulfur tax on coal, a reclamation tax on strip mining, smog devices on cars, and the cost of using low-sulfur oil or lead-free gasoline.[16] The environmental risks of nuclear power have not been quantified sufficiently to indicate whether nuclear power is underpriced, but the cost of safety is of concern to the nuclear industry, to regulators, and to opponents of nuclear power (124, 126, 127).

As public discussions of the risks and benefits of the various options indicate, environmental, safety, and social costs have come to dominate much of the concern (and research) regarding these technologies. Since these problems are largely excluded from the market system of prices, that system may be increasingly inappropriate to deal with energy problems. Internalizing the external costs of energy use will be a difficult political process because politicians and consumers alike will be faced with charging themselves for that which they apparently now get without costs: pollution.

It is difficult to imagine that appreciable conservation efforts will take place if energy prices continue to be controlled or rolled back, since few users will bother with the investment or the thought that is necessary to effect conservation. Voluntarism works well only for "the other guy." At the same time higher prices of energy, whether caused by real scarcity, monopoly power, fuel taxes, or environmental costs, are by no means an automatic cure by themselves for energy waste, because of the barriers to conservation discussed here.

Barriers to Efficient Energy Use

As costs of energy and systems change, different systems will be more economic (cheaper) than others. In a free market, each consumer will in theory adjust his energy use to the economic optimum, responding to price changes. Unfortunately economic systems, enterprises, entrepreneurs and private consumers cannot readily respond to changes in energy prices. To be able to do so energy users must have complete and accurate information about the energy and life-cycle costs of systems, and about the cost of energy embodied in various products. This information has been difficult to find. Recently labeling of appliances and automobiles has begun to raise both the consciousness and the level of available information about energy (135). The government has also aided homeowners and building owners by publishing several books of suggestions and conservation procedures as well as displaying the results from efforts in its own buildings (67, 136). Many utilities and fuel companies have done the same. Some industries using large amounts of energy, such as those in travel, plastics, and aluminum, take pains to measure and plan their energy use, but homeowners, small businessmen, and renters of office space can rarely afford this practice individually, and few understand the theory and practice of life-cycle costing, upon which economic efficiency depends heavily.

Most important, energy use is rarely a goal in itself but occurs in conjunction with other processes toward personal or economic ends. The price of energy is usually a small fraction of the cost of consumer goods (Table 13) or the cost of production (Table 14). The relatively low cost of energy compared with other expenses may mean that even where conservation is economic, the potential cost savings may be ignored.

The problems of sharply rising energy costs are particularly acute for energy-intensive industries addicted to unusually cheap or subsidized energy supplies (137). For airlines, the cost of fuel is now about 20% of the cost of doing business.[17] In these and other energy-intensive activities[18] the responses to higher energy prices—input juggling and thrifty technology—will be limited only by the time it takes to raise money and replace presently inefficient equipment. For example, the aluminum industry has a new process for producing aluminum from ore, which reduces energy requirements by one third (138). With the disappearance of low-cost electricity (the main ingredient in aluminum production besides the ore), smelters will turn more quickly to the new process even with its higher initial cost, because its life-cycle costs are lower.

The fact that energy consumption is so dependent on existing capital equipment is a general barrier common to all conservation strategies. If relative prices of certain foods change, consumers can

alter their demands on a day-to-day basis, independent of past expenditures or present possessions. On the other hand, energy use is largely pre-determined by the existing stock of devices and structures, so that a time lag can be expected between the rise in the price of energy and the response to conserve it. For a homeowner, the physical condition and design of the house and heating system, and the weather, determine how much heating fuel is needed to maintain a given indoor temperature. The homeowner can plug leaks and conserve fuel through improved maintenance, retrofitting of insulation devices, and use of warm clothes and lower temperatures, but the savings are usually smaller than those available if the house and furnace had been optimized (input juggled) in the first place. The same applies to large buildings. It is a fact that the energy savings possible from building energy-efficient structures in the future are as much as the total energy consumption of today's automobiles (15, 62) (Table 7). But while automobiles and industrial equipment tend to be replaced within ten years, buildings remain in use for decades or centuries. Thus if wastage of energy is built into structures, only feeble responses can be expected to the rising price of energy.

Even with complete information, it may not be possible for energy users to juggle inputs or plug leaks. Homeowners may not be able to choose homes (new or used) on the basis of energy fitness alone: families who move often are not in one home long enough for conservation to pay off to themselves; renters cannot easily add insulation to property they do not own, nor can they force landlords to insulate buildings if they, not the landlords, pay the utility bills. The same disadvantage hits small businessmen in large structures, where the utility bills are hidden in the rent. Industries affected by rising energy costs can pass those costs on to the consumer, especially if competition is limited or if the energy costs are small compared with the total value added, as is often the case.

Incentive barriers also exist for the production of energy-efficient equipment. Manufacturers have no incentive to produce energy-efficient autos or appliances if advertising, social pressure, consumer habits, or marketing procedures (such as rebates) give apparent advantages to less-efficient equipment. This holds especially if the buyer sees only the first cost, not the operation cost or life-cycle cost (see Figure 30). For refrigerators the energy costs are much larger than the purchase price (69, 71), but models packed with every feature (except insulation) tend to be advertised and sold on the basis of first cost alone. It was reported (139) that as of early 1975 buyers were largely still ignoring efficiency in selecting appliances, probably for the reasons cited here. Performance standards, which set minimum design efficiencies for energy-using equipment and structures, seem necessary to assure that systems surviving several owners or several generations are built efficiently in the first place. The advantage of performance standards is that systems in question operate efficiently, while the marketplace allocates the cost and savings of higher efficiency.

The problem of misplaced incentives hinders conservation in new buildings as well. Banks now have little incentive to lend extra money to make structures energy-tight, although utilities could refuse to provide services to inefficient structures. Developers will not risk the extra cost of insulation and other energy-conservation measures if competitors can omit the same, charge less, and obscure the differences with advertising (140, 141). Requiring efficiency standards on appliances and statements of heat loss through walls or limiting energy consumed per square foot in large buildings would assure that all developers and builders, as well as the banks that finance them, work under the same cost-effective constraint of energy effectiveness. The higher first costs, passed on to buyers and renters, would be more than repaid during the life of the structures or appliances.

The impact of higher prices for fuels on low-income groups cannot be ignored, and rebates have been suggested to aid these groups. But people earning more than about $10,000 per family require more energy indirectly for the goods and services they purchase than they do directly as heat, electricity, and gasoline. This means that the impact of energy costs is only mildly regressive with income (142) (see Figure 31). Some economists suggest that it is better to aid directly those who cannot afford expensive energy rather than make energy artificially cheap to all, which encourages everyone to waste energy.

President Ford has suggested an energy tax coupled with rebates that rise with income; this idea was lost in the debate over the antirecession program (143). Another alternative is a system of flat rebates, which distribute a nearly constant amount of money to all

families, under the assumption that well-to-do groups have more opportunities to improve efficiency, allocate resources more carefully, or simply do without certain luxuries such as airplane travel, second homes, recreational vehicles, or swimming pool heaters. This assumption appears to be borne out by Herendeen's work (Figure 31). Input-output data also suggest that price increases for energy will affect basic food and clothing and housing construction far less than luxury items such as large cars and travel.

Whether the economic barriers to efficient use discussed here can be overcome by legislative, institutional, or personal actions is of course an open question. Although economic models of energy use rarely consider these non-price variables in attempting to predict energy use, higher energy prices should stimulate energy users towards more optimal energy utilization. At the same time the effects of higher prices can be monitored and anticipated, as the input-output work cited here suggests. But society may want to conserve energy for non-market problems such as pollution, the effects of reliance on imported fuels, or the impact on the poor of expensive energy used inefficiently. Additionally, the nation may wish to implement conservation strategies at a faster pace than would occur in response to market forces alone. In these cases additional incentives for efficient use may be called for; some of these are discussed briefly in the next section.

Additional Incentives to Conserve

In addition to higher prices, incentives in the form of low-interest loans, tax benefits, rebates, or penalties, and other "carrots and sticks" should be considered carefully. The most common "stick" for encouraging more efficient energy use is higher prices, but bans on certain forms of consumption, rationing of fuels, voluntary quotas, and so forth are often discussed (143). At the same time "carrots" are receiving increasing attention; some are shown in Figure 32. Additional incentives to invest in energy conservation can come from the tax system. Governments can allow tax benefits for investments in energy-efficient equipment, provided that the investments are clearly aimed at efficiency. These incentives would include tax forgiveness in the increased valuation of property upgraded through conservation, tax credits or accelerated write-offs, and direct grants to those whose incomes do not allow setting aside capital for energy conservation.

Part of the cost of investing in conservation is interest, which is tax-deductible. For homeowners this interest is paid out of saved fuel and electricity costs, which are not tax-deductible. If conservation investments were added onto mortgages, the payments for which are interest-intensive during the first few years, the tax benefits would accrue early in the life of the investment. On the other hand, owners of apartments or factories deduct energy costs or pass them on in rents; for them direct tax credits for installing more efficient equipment may be necessary. Tax benefits should rise with increased efficiency, so that investment in efficiency well beyond the minimum required by standards would be encouraged.

Other Barriers to Efficient Energy use

Other economic difficulties inhibit energy conservation. The investment patterns required for the conservation measures discussed above mean that millions of small investments by consumers must take the place of relatively few large investments in energy facilities. The energy industry is experienced at accumulating capital, but the consumer and small businessman often struggle to make ends meet. This problem is especially acute for those on fixed or very small incomes. Governments should engage in conservation campaigns in which low-interest loans or grants are made available for clearly defined conservation investments. Sweden has already embarked on such a campaign to help finance the insulation of buildings (144).

A further barrier to conservation, perhaps one of the most difficult, is that consumers do not directly perceive some of the "hidden benefits" of conservation outlined here. Instead, these benefits accrue to society as a whole, through the millions of individuals who find more employment, cleaner air, lower energy prices, less congestion, better mass transit, and diminished threats to national security. Perhaps these common benefits need to be reinforced by taxes or subsidies, so that individuals can also perceive direct economic benefits to themselves from energy savings. Other benefits from more efficient energy utilization include lower world energy prices, and this can only be of help to the two thirds of the world that has not yet begun to realize the great social benefits that careful energy utilization brings (Figure 33). Last but not least, fossil fuels that are saved now will be available to future generations for use as chemical feedstocks.

The most often discussed reasons for conserving energy are the "necessity" to reduce oil imports and the desire to minimize threats to national security presented by interruption of fuel supplies (143).[19] Whatever the merits or problems of these two reasons, the derived benefits are difficult to quantify economically and do not accur directly to individuals. Policymakers include energy conservation as part of the overall national plan to reduce oil imports, yet this plan may not explicitly recognize that even without the problem of imports present energy use is far from economic.

Because economics favors more efficient energy use, it would seem that conservation has few opponents. On the other hand, the energy industry is threatened with slower growth than at any other time since the Depression (145). As noted above, some industry spokesmen or organizations have continually endorsed the need to continue historical growth in energy use (24, 25).[20] This is particularly true for some electric utilities. Under the name "People at America's Investor-Owned Electric Companies," one group has stated that growth in electric power consumption at historical rates is beneficial and inevitable, as Figure 34 illustrates. The claims of advertisements such as this have been challenged elsewhere (147-149), and it has been noted that they have seldom carried any suggestions about energy conservation. However, other utilities have now begun earnestly to tell subscribers how to conserve electricity and gas, as Figure 32*D* shows.

It has been suggested that if utilities were to engage in the selling of comfort systems, rather than only of energy, they would find a greater incentive to participate in energy conservation programs. In this idea, the utility would own and maintain the entire energy system in a structure and lease it to the firm or individual. One utility (159) now installs insulation in residential property and allows owners to pay off the investment on the same bill as for natural gas. Another arranges for outside financing and installation (W. Zitlau, San Diego Gas and Electric Company, 1974, private communication). The degree to which the energy industry participates in energy conservation R & D and implementation will appreciably influence the future demand for energy.

The very notion that energy is being used inefficiently that Americans must husband resources and eke out the next unit of welfare from higher efficiency rather than higher gross inputs, suggests a confrontation between aspects of the traditional American way of life and the true finiteness of the world vis-à-vis the rates of use of resources. As is often noted, energy prices fell for many years while the side effects of cheap energy use—pollution, urban sprawl, decay of the mass transportation system, the endless substitution of energy for other production factors—became a part of that way of life. Now American society, and indeed the world, is faced with the prospects of intervening in these trends in order to use energy more efficiently, not because society has run out of energy, but because society is having difficulty even running at today's rate of use. The distribution of energy usage in the world (Figure 33) shows clearly that most of the world has not begun to realize the social benefits of energy, while part of the world struggles with the side effects and economic dangers of the wasteful use of energy (151).

To some, the challenge for changes in energy utilization might be interpreted as some kind of threat to the American economic system. To me, however, the need for energy conservation must be interpreted as a fortunate signal. Indeed while man's physical activities and uses of resources are rate-limited,[21] (151) both technical and social changes in structure and operation of systems are possible which will allow us to win more social benefit from increasingly scarce resources. The hope for "cheap nuclear fission," or "cheap solar energy," none of which is in fact cheap, constantly distracts individuals and institutions from making economic adjustments now to more efficient energy use and obscures the possibility that nature has, in reality, imposed a kind of speed limit on our activity.

SUMMARY

The role of energy in an economy can only be understood through consideration of both an economic description of energy imputs and outputs and a physical analysis of the activities in the economy that use energy. Such analysis leads to several definitions of energy efficiency, waste, and conservation, definitions that are sometimes, but not always, close to those of traditional economics. Conserving natural resources for future generations, or for those who cannot afford them today, and preserving environmental quality are important reasons for conserving energy. But economic analysis of the physical options for energy conservation shows that saving 30-40% of the otherwise expected future total energy demand

in the United States would be far less expensive than supplying the increased amounts of fuels and electricity dictated by naive extrapolation of historical trends.

Conservation strategies also tend to increase employment and decrease pollution, while saving energy and money. By easing demands on dollar and energy capital required to build and run energy-producing facilities, conservation alows the real rise in the cost of energy. However, conservation faces a full range of important nontechnical problems, which are rooted in the history of energy utilization at low energy prices, as well as barriers connected with defects in the pricing of energy, the control of the end use of energy, and the time necessary for society to adjust to sharply rising energy costs.

A variety of social, political, economic, and technical changes are often suggested as remedies for today's energy problems (96, 142, 143, 151-156).[22] These include decontrol of fuel prices, energy taxes, rationing or allocation, subsidies or low-interest loans for efficient use, bans on certain end uses or social activities, and educational programs designed to change people's attitudes. Energy policy designed to encourage efficient use of energy will probably have to incorporate many of these measures, using both traditional and novel market and non-market tools. Even before considering the question of what sources of energy to develop tomorrow, one must confront energy conservation today: inefficient energy use means inefficient and costly malfunctions in the US economy. Perhaps recognition of the influential role of energy waste in exacerbating our economic and environmental problems will aid progress toward more efficient energy utilization.

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Footnotes

[1]For reviews see other articles in this volume or the April 19, 1974 issue of Science. For "alternative" source see (4).

[2]An excellent introduction to the physics of energy can be found in (19).

[3]An excellent introduction to economics of resources and pollution can be found in (22).

[4]See the general discussion of future demand in (24). Cook & Vassell (25) largely ignore conservation techniques.

[5]See review by Criag, Darmstadter & Rattien in this volume.

[6]See also the Appendix in (43) for sample calculations.

[7]The matter of net energy during period of growth in the nuclear program has not been settled.

[8]Information released by Pennsylvania Power and Light Company, Allentown, Pa.

[9]See footnote 8.

[10]See discussion and references in (45). Also see (93).

[11]See (101). The BART electric train system in the San Francisco Bay Area underscores one dilemma in the interaction of urban planning, geography, and energy use: If a rapid rail system stimulates commuters to live farther from work than they otherwise would, some or all of the energy conservation benefits of this system would be lost.

[12]See (82) for a comparison of costs of fueled and solar systems in various locations. It is generally anticipated that solar heating/cooling systems will fall in cost through economies of scale in manufacture as well as through technological advances.

[13]J. Holdren, personal communication. These numbers are easy to calculate. Heat pumps are becoming increasingly common in areas where electric resistance heating is appreciable, like the TVA service territory (105).

[14]See the discussions in (21) or (114). It is important to consider the various costs associated with different levels of "clean" in production from "new" sources. As Figure 24 suggests, these costs will also rise with the level of use of "new" sources.

[15]Page (23) discusses some of the difficulties of applying economics to environmental problems that stretch out over decades or centuries.

[16]Reader should consult the transcripts of hearings held by Congress. The Committees on Commerce or Interior and Insular Affairs are the most active in the Senate, whereas the Committees on Science and Astronautics, Ways and Means, Interior and Insular Affairs, and the Subcommittee on Energy and Power of the House hold most of the energy hearings where policy is debated. In addition to these committees, the Senate Committee on Public Works has debated most of the important environmental policy issues.

[17]The major airlines sent telegrams to President Ford after his announced intention (January 1975) to "free" oil prices. The airlines asked for a percentage quota of their 1973 fuel use—at controlled prices—instead of the higher prices that the President's action would have allowed.

[18]The average dollar of expenditure for personal consumption requires about 80,000 Btu.

[19]See footnote 16.

[20]For a view supporting the aggressive promotion of load growth in electricity use, see (146).

[21]See (151).

[22]See also footnote 16.

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Table 1 The laws of thermodynamics[2]

<u>First Law of Thermodynamics</u>

Energy can be neither created nor destroyed, but it can change form. ("You can't get something for nothing, you can only break even.")

<u>Second Law of Thermodynamics</u>

It is impossible to convert a given quantity of heat completely into work. In any macroscopic process involving energy conversion, some energy is always degraded in quality, so that ability to do work is lessened. ('You can't break even, you can only lose.")

Quality of energy described the degree to which energy can be converted into work, which is the application of force through a distance. The quality of thermal energy increases with the temperature <u>difference</u> between the body of heat and the background environment. Work, electricity, and gravitational energy are of the highest quality; chemical energy stored in fuels is also of high quality, although not the highest. The first law merely states that the total quantity of energy in a closed system is conserved. The second law, however, asserts that the quality of energy can be consumed in physical processes.

[a]See (19) or chapter by C. A. Berg in this volume.

Table 2 Residential energy consumption of the largest metropolitan areas in the United States[a]

Rank	Metropolitan Area	Thousands of Btu per Degree-Day	Rank	Metropolitan Area	Thousands of Btu per Degree-Day
1.	San Diego	72	21.	Detroit	33
2.	Los Angeles	63	22.	Dallas-Ft. Worth	31
3.	New Orleans	60	23.	Providence	31
4.	Phoenix	55	24.	Oklahoma City	31
5.	Houston	55	25.	Dayton, Ohio	30
6.	New York City	55	26.	Buffalo	29
7.	Chicago	44	27.	Columbus, Ohio	27
8.	Newark	39	28.	Baltimore	26
9.	Washington, D.C.	37	29.	Denver	26
10.	San Antonio	37	30.	Rochester	25
11.	Louisville	36	31.	Boston	25
12.	San Francisco	36	32.	Philadelphia	25
13.	Indianapolis	36	33.	Portland, Oregon	24
14.	Pittsburgh	36	34.	Kansas City	24
15.	Cleveland	36	35.	Minneapolis	24
16.	Memphis	35	36.	Seattle	23
17.	Atlanta	34	37.	Milwaukee	20
18.	Cincinnati	34	38.	Birmingham	20
19.	St. Louis	33	39.	Hartford	17
20.	Norfolk	33[b]			

[a]Source: (42)

[b]Median consumption

Table 3 American Physical Society estimates of efficiency of energy use[a]

Use	Relative Thermodynamic Quality	Percent of US Fuel Consumption (1968)	Estimated Overall Second-Law Efficiency
Space heating	Lowest	18	0.06
Water heating	low	4	0.03
Cooking	low	1.3	--
Air conditioning	lowest	2.5	0.05
Refrigeration	lowest	2	0.04
Industrial uses			
Process steam	low	17	0.25
Direct heat	high	11	0.3
Electric drive	high	8	0.3
Electrolytic processes	high	1.2	--
Transportation	highest		
Automobile		13	0.1
Truck		5	0.1
Bus		0.2	--
Train		1	--
Airplane		2	--
Military and other		4	--
Feedstock		5	--
Other		5	--
		100	

[a]Source: (45).

[b]Work is defined as Infinite-temperature energy by the APS study.

Table 4 The energy cost of some common goods and services[a] the energy costs associated with the production and recycling of metals.[b]

1967 Example Energy Intensities[c] Product	(10^3 Btu/$)	Summary of the Energy Requirements for the Production and Recycle of Metals[c] Metal	Main Source	Equivalent Coal Energy (kWh/ton)
Primary aluminum	388	Magnesium	sea water	90,821[103,739]
Fertilizers	174		mg scrap recycle	1,395[1,875]
Airlines	192			
Glass	103	Aluminum	bauxite 50% alumina	51,379[63,892]
Motor vehicles	67		aluminum scrap recycle	1,300-2,000
Cheese	73			
Apparel	50			
Hospitals	51	Iron	high-grade hematite	4,270[4,289]
Computing machinery	36		iron laterites	6,268[6,327]
Banking	18		iron and steel scrap recycle	1,240[1,666]
US average				
Including energy	80			
Non-energy goods	52	Copper	1% sulfide ore	13,532[15,193]
			0.3% sulfide ore	24,759[29,766]
			98% scrap recycle	635[853]

[a]Source: (52) These are direct plus indirect energy requirements.

[b]Source: (87). These are direct requirements only.

[c]Electricity has been counted at 40% conversion from fuel to electricity

[d]Figures in parentheses count electricity at 29% efficiency.

Table 5 Energy cost of energy: efficiency of the U.S. economy in delivering energy, 1967[a]

Sector	Efficiency (%)
Coal	99.3
Refined petroleum,	82.8
Electricity	26.3
Natural gas	90.9

[a]Source: (52). Percentage of total Btu's harvested by the energy industries that are delivered to the US economy.

Table 6 Kinds of energy conservation[a]

IN EXISTING SYSTEMS

Leak Plugging

Reducing heat and cooling losses in life-support systems, adjusting energy systems that are not running at design efficiency, and eliminating unutilized or underutilized energy by retrofit in all energy systems. Examples include insulation in buildings, heat recovery in industry. Leak plugging techniques are generally implemented once, at little initial cost, and then remain passively effective.

Mode Mixing

Changing the mix of transportation to utilize modes requiring less energy per passenger- or ton-mile.

Energy Management

Turning off lights, heat, or cooling; changing thermostat settings; improving maintenance; driving more slowly; car-pooling; increasing load factors in public transportation. Involves small but important changes in energy use. May cause minor changes in life-style and habits. Energy management, unlike leak plugging, must be actively pursued by individuals or firms. Capital costs are usually small. Also called "belt tightening".

IN NEW SYSTEMS

Thrifty Technology

Introduction of innovative technology not in common usage in any energy system to increase the useful output of the system per unit of energy consumed. Examples include gas heat pumps for space and industrial heat, electric ignition of gas water heaters, or new propulsion systems in transportation.

Input Juggling

Change in the mix of existing economic or physical inputs to a given kind of output. Substitutions can be among energy forms or among economic variables such as labor, capital, design (a form of capital), and machines. Solar energy substitutes capital and labor for heating; returnable bottles substitute labor for the extra energy and materials requirements of throwaways.

Output Juggling

Changes in life-style, consumer preferences, investment practices, or shifts from manufacturing to services in the economy, which lead directly and indirectly to lower (or higher) energy requirements. Shifting to throwaway containers raises energy requirements per unit of beverages. Gardening at home instead of taking a Sunday drive lowers energy use. Smaller cars, changing urban housing patterns, increased vacationing closer to home are all examples of output juggling.

[a]Modified from (14).

Table 7 Applying some energy conservation strategies: possible savings[a]

Area of Strategy	Potential Savings[b]	Notes	References
HOMES, BUILDINGS			
Space heating	5-8%	Insulation; heat pumps cut electric heating needs by 50%; gas heat pump a possibility	51, 62, 63, 64, 65, 66, 67
Air conditioners	>1%	Save peak power: fewer brownouts; insulation, design, window improvements reduce heat load	43, 79, 68, 62, 65, 66
Home appliances	2%	Fluorescent lights, better motors, and insula tion in water heaters, electric igniters replace pilot lights	44, 69, 70, 71 72, 73
Design of buildings	5%	Includes redefining lighting levels and tasks; total energy systems, conserving window systems; orientations that reduces energy needs	74, 75, 76, 77 78, 73, 79, 90
Solar heating cooling	10%	If 40% of today's heating and cooling were solar; Economics depends on cost of glass, storage, and alternative fuels	62, 75, 81 82
Total 1973 US demand: 30×10^{15} Btu. (Ross & Williams, Ref. 62)		Hypothetical demand with maximum savings: 18×10^{15} Btu.	
INDUSTRY			
Process heat	5-12%	Once through the facility is sufficient, with insulation, leak plugging; more sophisticated treatment requires redesign, pipes, cascading high-temperature processes with lower temperature demands	68, 83-86
Total energy: cogeneration of electricity and heat at factory	3-5%	Energy independence to factories; siting communities near industries is a possibility	45, 47, 62
Returnable bottles, recyclable materials use	1-3%	Many institutional problems as "no deposit, no return" becomes ingrained	54, 87, 88, 89 +
Total 1973 US demand: 26×10^{15} Btu. (Ross & Williams, Ref. 62)		Hypothetical demand with maximum savings: 14.5×10^{15}	

Table 7 Applying some energy conservation strategies: possible savings[a] (cont)

Area of Strategy	Potential Savings[b]	Notes	References
TRANSPORTATION			
100% shift to 40% lighter cars	5%	Appreciable savings in energy cost of building car, refining oil; less pollution, with less traffic	37-30, 45 39-41, 47 91, 92
More careful driving cycle	1%		
Improved technical efficiency of autos	5%		
Switch one half of urban pass miles to bus	2%		
Improved load factors, in rail, bus, plane, mass transit	2%	Savings in freight and other passenger modes come mainly from fuller utilization of existing routes and higher load factors	93, 94, 6 91, 92 37-39
Freight mode improved technical efficiency	2%		
Total US 1973 demand: 19×10^{15} Btu. Hypothetical demand with maximum savings 10×10^{15} Btu. Note that transportation is nearly 100% dependent on liquid fuels.			
OTHER			
More durable repairable, and recyclable goods	?	Substitutes quality work for endless throwing away	13, 33, 50 95, 96
Urban design	?	Live near work, district heating, etc	
Changes in consumer preferences	?	"Output Juggling"—vacation near home, ride a bike, work in the garden	

[a]Source: (14, 15, 62) and references cited.

[b]Given in percentage savings of total use (early 1970s). Savings figured as optimum achievable at 1980 energy prices. Individual savings do not add. See also (6-16, 62).

Table 8 Identified savings potential of eight industrial plants[a]

Plant Type	Total Annual Energy Bill[b]	Identified Savings[b]	Percentage
Basic chemicals	5.5	2.39	43.4
Textiles	.9	.29	32.0
Agricultural chemicals	1.7	.28	16.7
Oil refinery	10.3	1.12	10.8
Chemical intermediates	13.2	1.87	14.2
Food processing	1.1	.33	30.1
Pump and paper	5.3	1.70	31.5
Rubber and tires	2.9	.47	16.4
Average	$ 5.1	$ 1.05	20.6

[a]Source: E. I. Dupont 1973 Energy Management Client List (83).

[b]In millions of dollars.

Table 9 Efficiency and the cost of air conditioning[a]

Rated Cooling Capacity (Btu/hr)	Rated Current Demand (A)	Retail Price $	First-Law Efficiency[b] (Btu/W-h)	Ten-Year Total (dollars/1000 Btu)
4000	8.8	100	3.96	84.
	7.5	110	4.65	77.70
	7.5	125	4.65	81.45
	5.0	135	6.96	67.25
5000	9.5	120	4.58	74.90
	7.5	150	5.80	68.20
	7.5	150	5.80	70.20
	5.0	165	8.70	59.80
6000	9.1	160	5.34	67.30
	9.1	170	5.24	68.90
	7.5	170	6.96	61.80
8000	12	200	5.80	67.30
	12	220	5.80	67.80

[a]Cost of air conditioning is inversely proportional to first-law efficiency. In each class of air conditioner, the model with the highest first-law efficiency has the lowest yearly cost. Examples worked out by Berg (68).

[b]Also called energy efficiency ratio (EER).

Table 10 Cost and energy savings of key design elements in all-electric homes[a]

Item	Extra Cost ($)	Annual Savings (kW-hr)	Investment per kW-hr/yr saved
Styrofoam roof insulation	930		
5-Foot overhang	1026		
Styrofoam wall insulation	375	2000	65¢ (insulation only)
Casement windows and french doors	800		
Door closers	80		
Single 3-ton water-to-air heat pump (design b)	1000	5420	20¢
Hot gas-water heater	300	3240	10¢
Refrigerator	100	650	15¢
Range	400	300	Self-cleaning, no charge
Dishwasher			
Air heater	25	110	12¢
Short wash		210	
Clothes washer	70	340	20¢
Dryer and clothes line	50	300	16¢
Freezer	50	300	16¢
Trash bins	(Save 130)	50	--
Fluorescent lightning	(Save 430)	840	--
Total	4646	13,700	

[a]Source: (74). Figures based on an all-electric home in Florida.

Table 11 Energy and labor intensities of the top 20 (dollarwise) personal consumption activities in 1971[a]

Personal Consumption Expenditure—Sector Description	Energy Intensity (Btu/$)	Labor Intensity (Jobs/$1000)
Electricity	502,473	0.04363
Gasoline and oil	480,672	0.07296
Cleaning preparations	78,120	0.07332
Kitchen and household appliances	58,724	0.09551
New and used cars	55,603	0.07754
Other durable house furniture	45,493	0.08948
Food purchases	41,100	0.08528
Furniture	36,664	0.09176
Women and children's clothing	33,065	0.10008
Meals and beverages	32,398	0.08756
Men and boys' clothing	31,442	0.09845
Religious and welfare activity	27,791	0.086365
Privately controlled hospitals	26,121	0.17189
Automobile repair and maintenance	23,544	0.04839
Financial interests except ins. co.	21,520	0.07845
Tobacco products	19,818	0.05845
Telephone and telegraph	19,043	0.05493
Tenant occupancy, non-farm dwelling	18,324	0.03258
Physicians	10,271	0.03258
Owner occupancy, non-farm dwelling	8,250	0.01676
Average, including energy purchases	70,000	0.08000
Average, non-energy purchases only	52,000[b]	--

[a]Source: (100)

[b]1967 figure. The corresponding 1967 figure for average including energy was 80,000 Btu/$. Source: R. Herendeen, private communications.

Table 12 Net energy output from various synthetic fuel processes[a]

Process	Lurgi-Gas	Hygas	CSF-Coal Process	Coal-Methanol	Shale-Syncrude
Percentage of Btu's recovered in desired form	56.2	59.7	55.0	39.6	66.5
Other by-products by Btu content	15.3	8.2	12.2	1.5	7.4
Total	71.5	68	67	42	73

[a]Source: (123). The estimates do not include energy expenditures for capital equipment or harvesting (earth moving, crushing, water supply), nor are transportation energy requirements given. Figures are percentages of Btu-inputs.

Table 13 The energy content of selected goods and services in 1971[a]

Product	Energy Content (Btu/$)	Gasoline Equivalent (gal)	Energy Value Content (¢/$)
Plastics	218,097	1.74	13.2
Man-made fibers	202,641	1.62	7.4
Paper mills	177,567	1.42	7.9
Air transport	152,363	1.22	12.0
Metal cans	136,961	1.10	7.3
Water, sanitary services	116,644	.93	11.6
Metal doors	109,875	.88	6.7
Cooking oils	94,195	.75	7.1
Fabricated metal products	91,977	.74	5.8
Metal household furniture	91,314	.73	5.9
Knit fabric mills	89,991	.72	6.5
Toilet preparations	85,671	.70	5.1
Blinds, shades	81,472	.65	6.3
Floor coverings	79,323	.63	5.8
House furnishings	75,853	.61	5.3
Poultry, eggs	75,156	.60	7.3
Electric housewares	74,042	.59	5.6
Canned fruit, vegetables	72,240	.58	5.2
Motor vehicles and parts	70,003	.56	5.9
Photographic equipment	64,718	.52	3.8
Mattresses	63,446	.51	4.5
New residential construction	60,218	.48	4.5
Boat building	60,076	.48	4.9
Food preparation	58,690	.47	4.8
Soft drinks	55,142	.44	4.5
Upholstered household furniture	51,331	.41	4.1
Cutlery	50,021	.40	4.0
Apparel, purchased materials	45,905	.37	4.0
Alcoholic beverages	43,084	.34	3.0
Hotels	40,326	.32	5.4
Hospitals	38,364	.30	5.4
Retail trade	32,710	.26	4.4
Insurance carriers	31,423	.25	4.4
Miscellaneous professional services	26,548	.21	4.3
Banking	19,202	.15	2.5
Doctors, dentists	15,477	.12	1.9

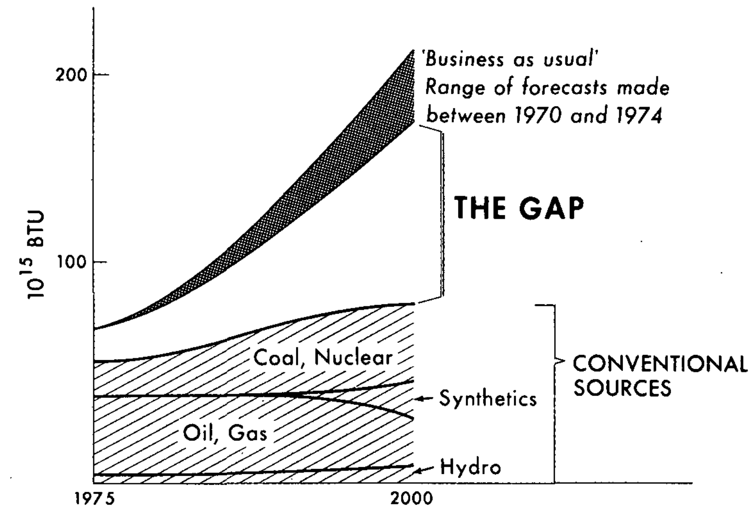
[a]Source: (136a). These values are for producers' prices and do not take into account markup to retail price, about 66%.

Table 14 The cost of electricity as a percentage of production costs: US manufacturing industries 1939-1967[a]

Industry	Cost of Purchased Power (% of Product Value) 1939	1967
Primary metal industries	1.8	1.8
Fabricated metal products	--	0.6
Chemicals and allied products	2.0	1.7
Paper and allied products	3.9	1.9
Food and kindred products	1.1	0.4
Transportation equipment	0.7	0.4
Petroleum and coal products	1.2	0.8
Stone, clay, and glass products	3.2	1.5
Textile mill products	2.3	0.9
Electrical machinery	1.1	0.5
Machinery, except electrical	0.9	0.5
Rubber products	1.6	1.0
Lumber and wood products	1.8	0.9
Printing and publishing	0.8	0.4
Apparel and related products	0.4	0.3
Instruments and related products	--	0.4
Furniture and fixtures	1.0	0.5
Leather and leather products	0.6	0.4
Tobacco manufactures	0.2	0.2
Miscellaneous manufactures[b]	0.9	0.4
All manufacturing	1.41	0.79

[a]Source: Edison Electric Institute, 1973

[b]Includes ordinance and accessories.



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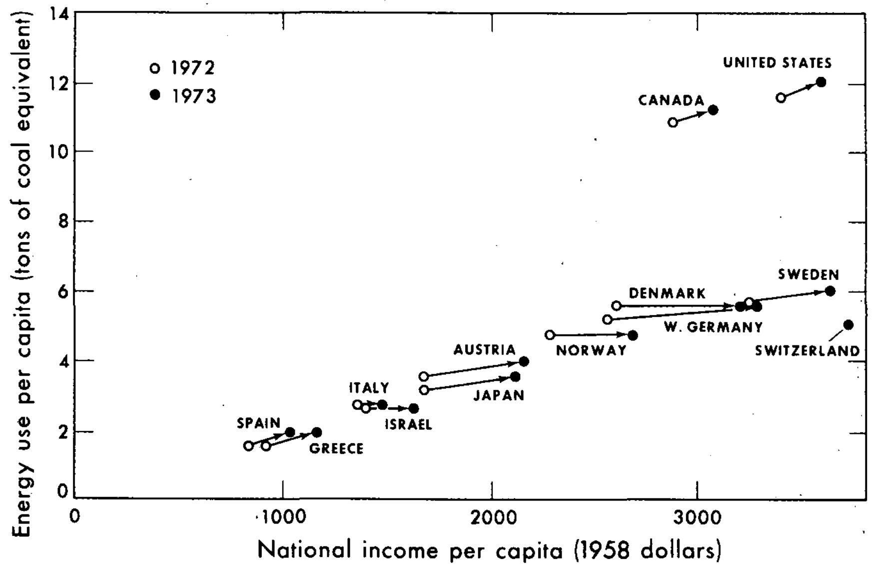

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Figure 1. The energy gap. In conventional forecasts domestic energy supply lags behind demand that grows at the historical rate of about 4-5% per year. Compare with forecasts in (1-3).

Figure 2. Per capita energy use and national income of some important industrial and emerging nations, 1972 and 1973. Note the wide variation in energy use among the nations with highest per capita income, measured in 1958 US dollars at current exchange rates. Data for Switzerland based on author's estimate.

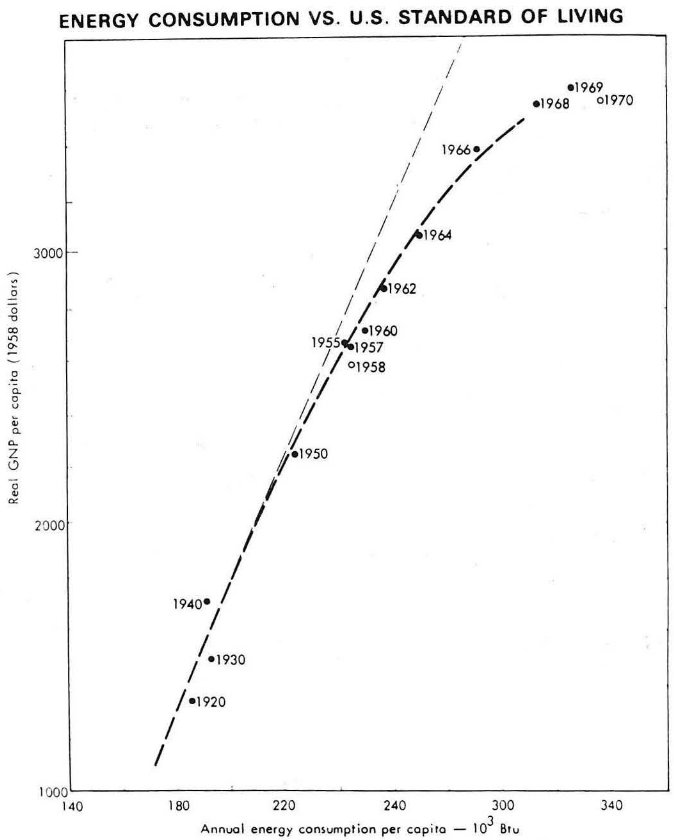

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Figure 3. Growth of energy use and GNP in the United States. Source: (27).

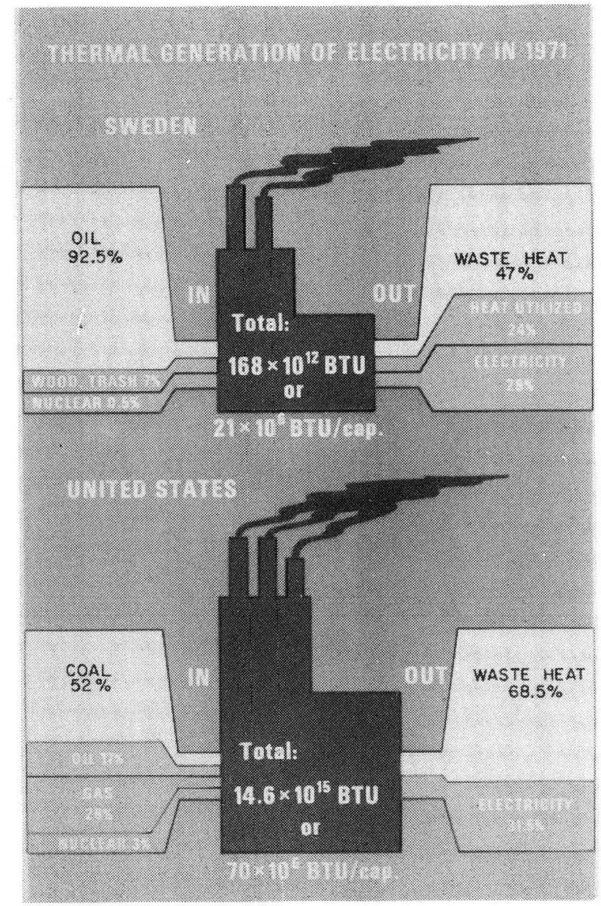

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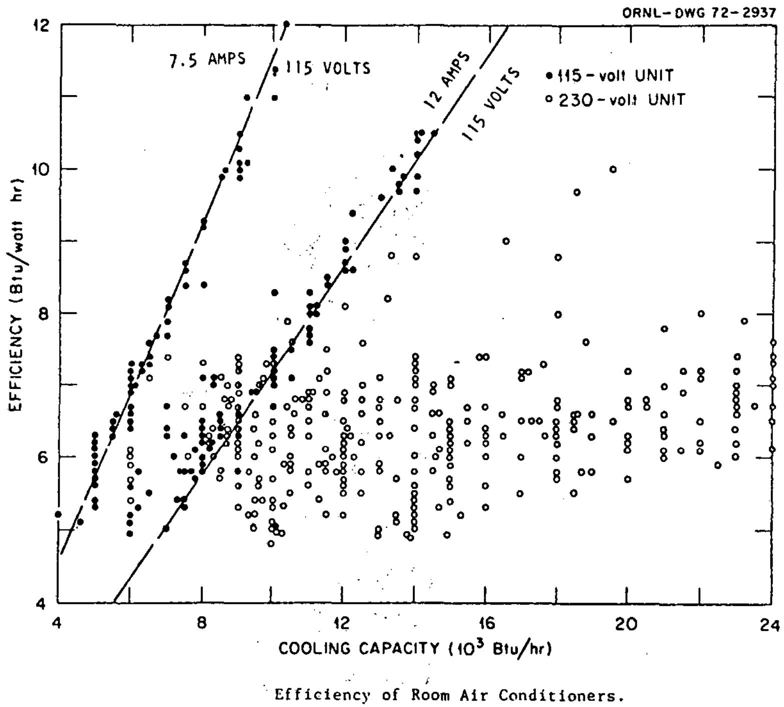
Figure 4. Comparison of utilization of output from thermal electric power plants in Sweden and the United States in 1971. Source: (14, 33).



XBL 759-8026

Figure 5. First-law efficiency of air conditioners. Vertical axis gives heat removed per unit of energy consumed; horizontal axis, the size of the unit. Note the wide variations in efficiency. The models that lie near the two straight lines are those constrained to operate on either 7.5-amp or 12-amp circuits. Source: (43).

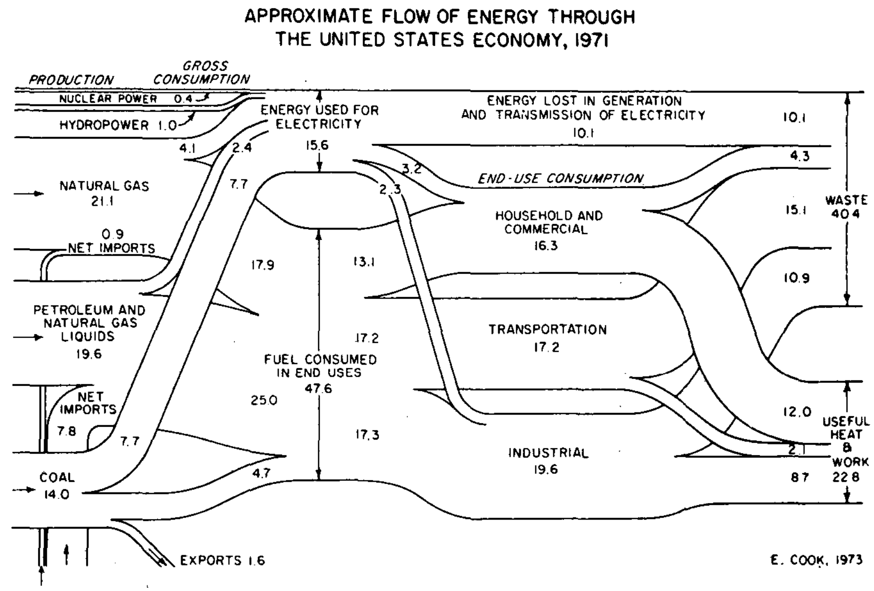


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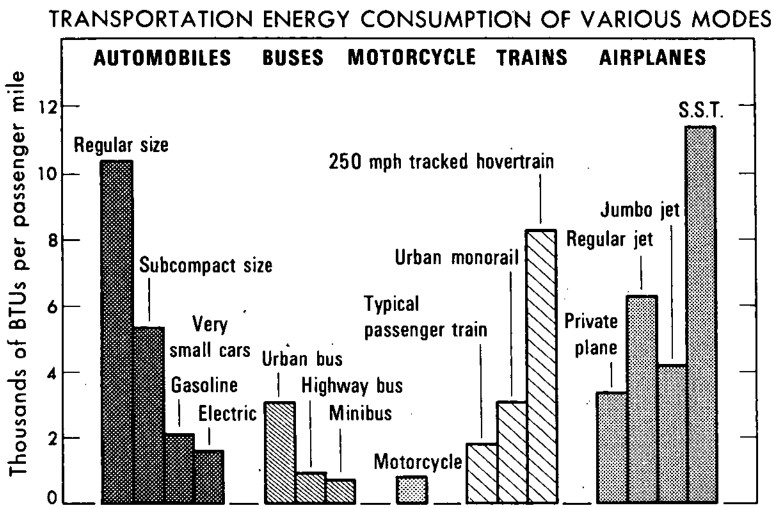
Figure 6. First-law efficiencies of energy use in the United States in 1971. Estimates by E. Cook, Ref. 21. In Cook's earlier "spaghetti bowl," drawn for a variety of scenarios in (46), overall first-law efficiency was assumed to be higher, around 50%.



XBL 759-4097

Figure 7. Design intensities of some modes of transportation, in Btu per passenger mile, using common load factors. Data from R. Rice, presented in (7). Note the wide variation in design, intensities, which are far lower than possible in most cases because of low load factors.

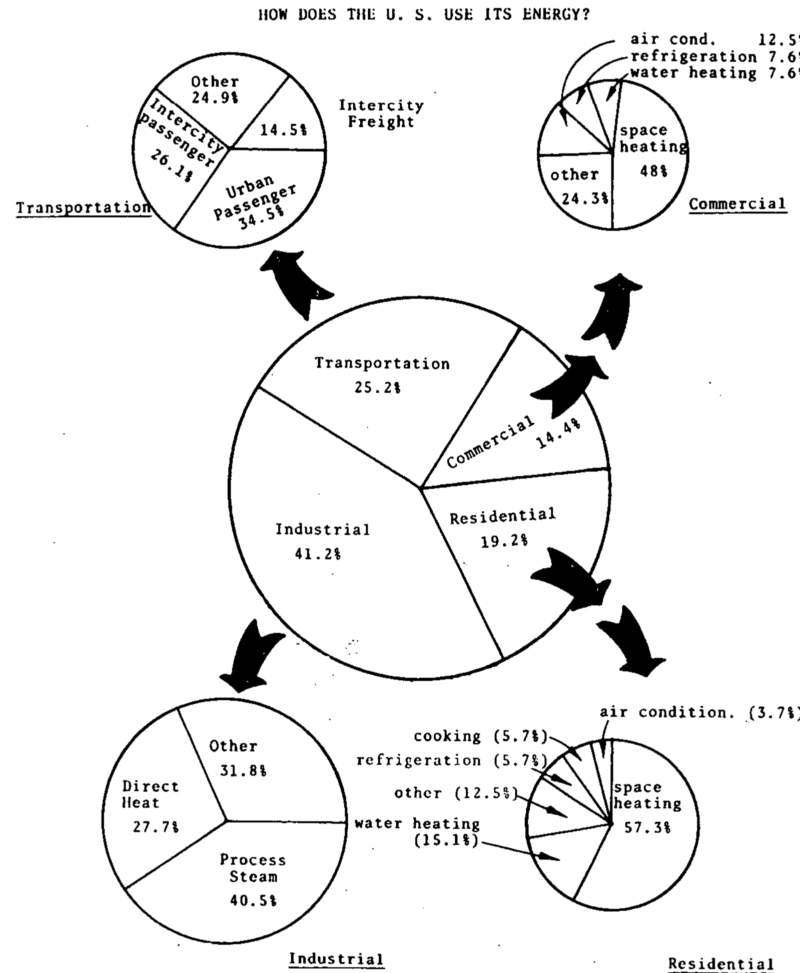


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Figure 8. How does the United States use its energy? Schematic pie representation of energy uses in the United States. From Oak Ridge Associated Universities, 1974, Citizens Energy Workshop Handbook, Oak Ridge, Tenn. Compare with Table 3 and Figure 6.

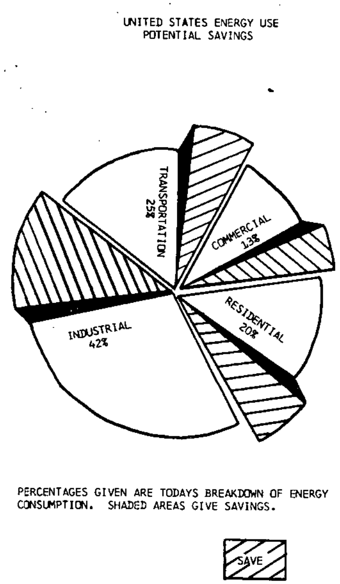

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Figure 9. The energy pie of Figure 8, with savings summarized in the four sectors. Percentages given are today's breakdown of energy consumption. Shaded areas give savings. Source: (14) and Table 7.

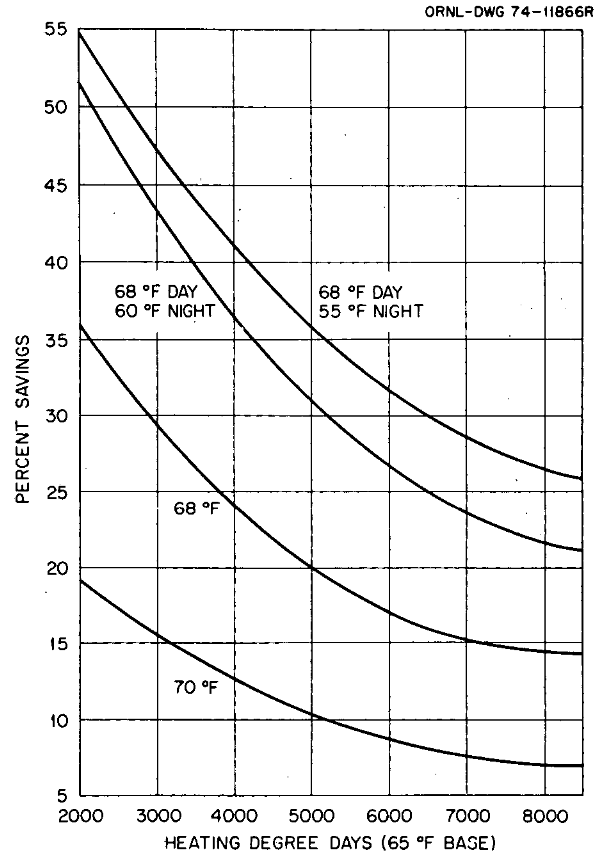

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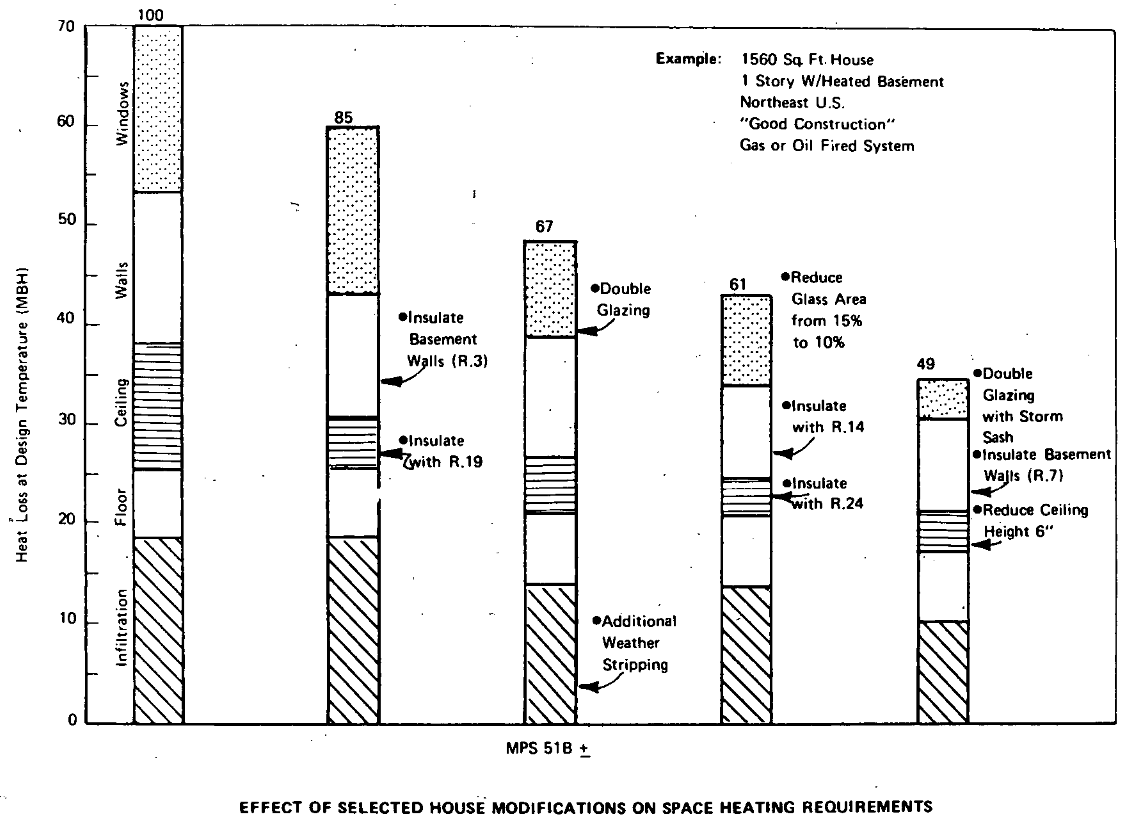
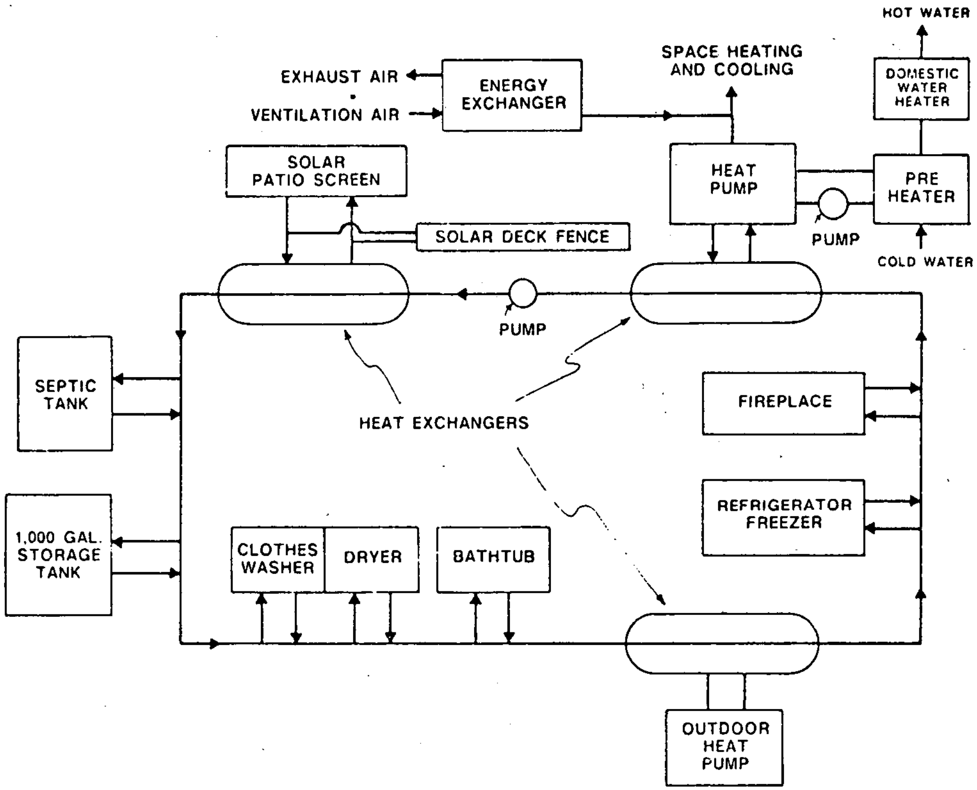
Figure 10. Management: predicted energy savings for several thermostat settings. (72° F is the reference setting, and night setback is from 10 PM to 6 AM.)



XBL 758-7939

Figure 11. Leak plugging and input juggling: effect of more elaborate modifications of design and construction of a house on energy use for heating. Note the progressive savings. Source: (67).

0 0 0 0 4 2 0 3 6 3 5



Schematic of house of the future.

XBL 759-8023

Figure 12. Input juggling and thrifty technology: schematic of the house of the future. This system is installed in the experimental low-energy house built by Pennsylvania Power and Light Company in Allentown, Pa. Heat exchangers recapture as much heat as possible.

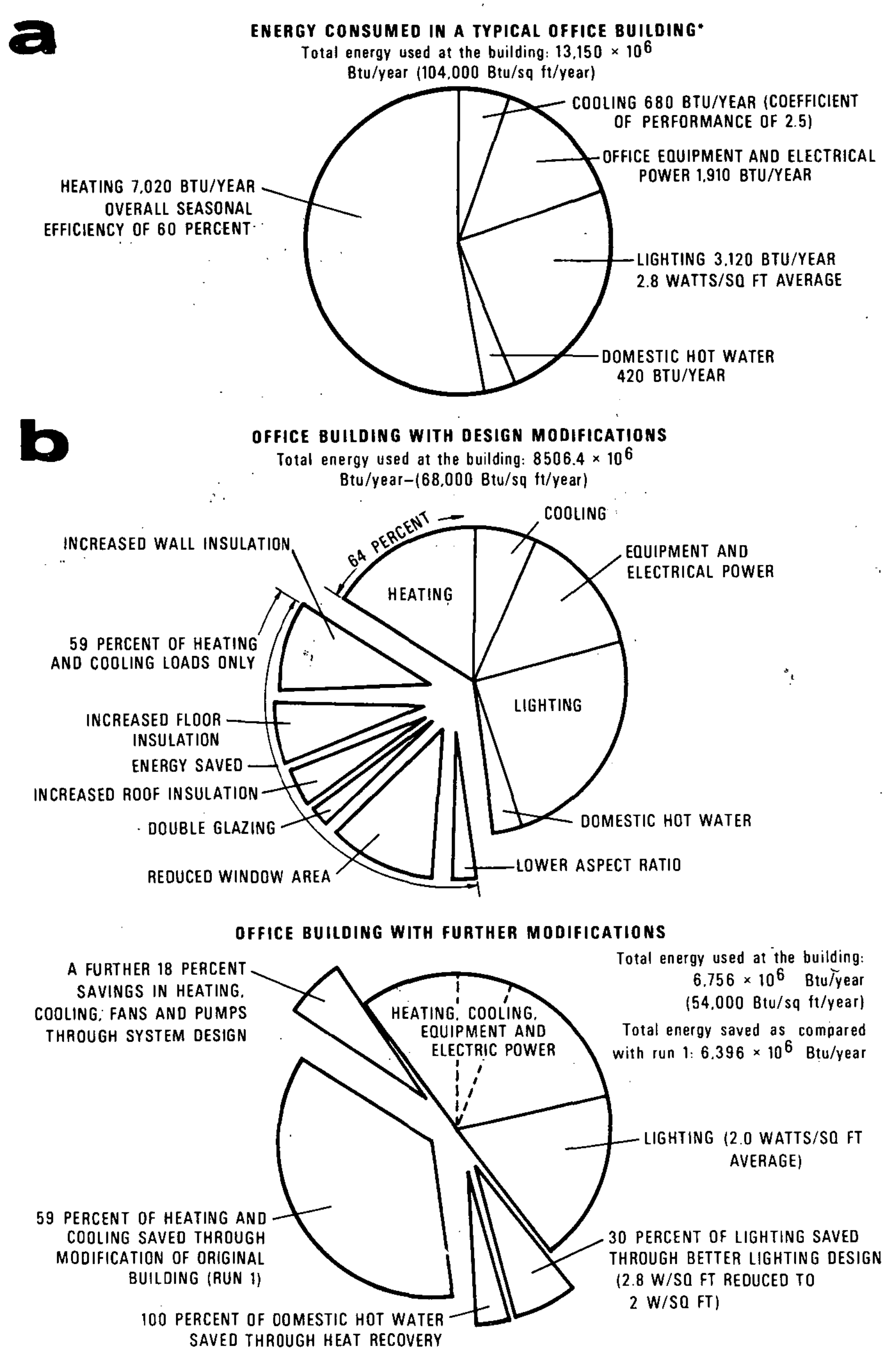


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Figure 13. All strategies: effect of progressive design modifications of an office building. Actual predictions of building being built for Government Services Administration, in Manchester, NH. Source: (77). Figures show equivalent energy units of 10^6 Btu/year.

(a) In New England; 126,000 sq. ft.; design based on "typical" New England design criteria; weather data from Manchester, NH: wall U value = 0.3 Btu/° F-hr-ft; floot U value = 0.25; roof U value = 0.2; single glazing, 50% window/wall area ratio; shading coefficient = 0.5 (year round); 6 stories tall; 2:1 aspect ratio (length:width); long axis, north-south.

(b) Wall, floor, roof U values = 0.06; double glazing, 10% window/wall area ratio; shading coefficient = 0.5 (year round).

0 0 0 0 4 2 0 3 6 3 6

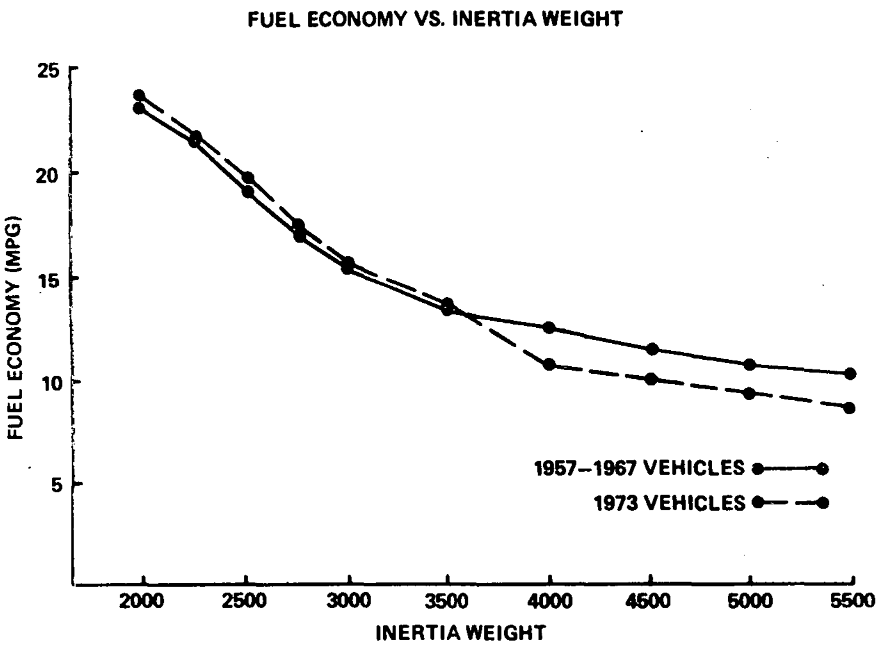

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Figure 14. Design efficiencies: fuel economy vs. inertial weight. The design efficiency of lighter cars is obvious. Source: (94).

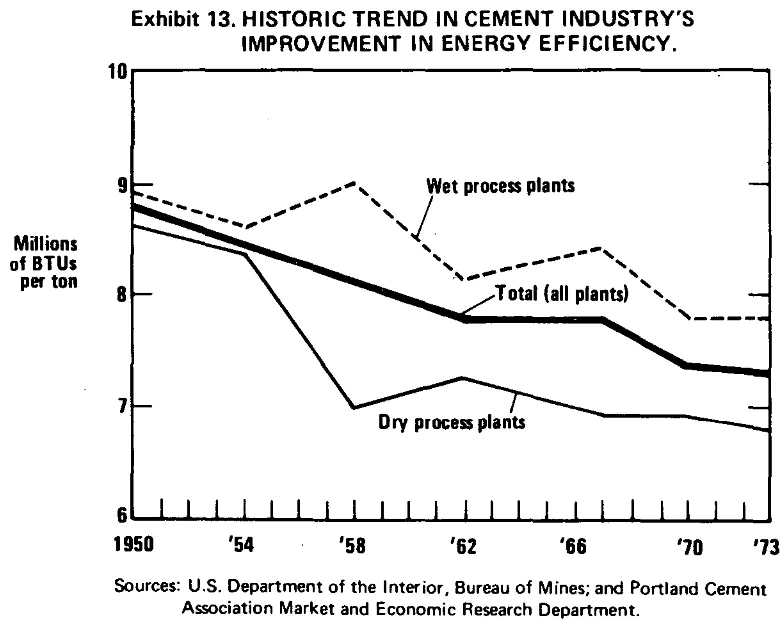

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Figure 15. Historic trend in the cement industry's improvement in design efficiency. Source: (102).

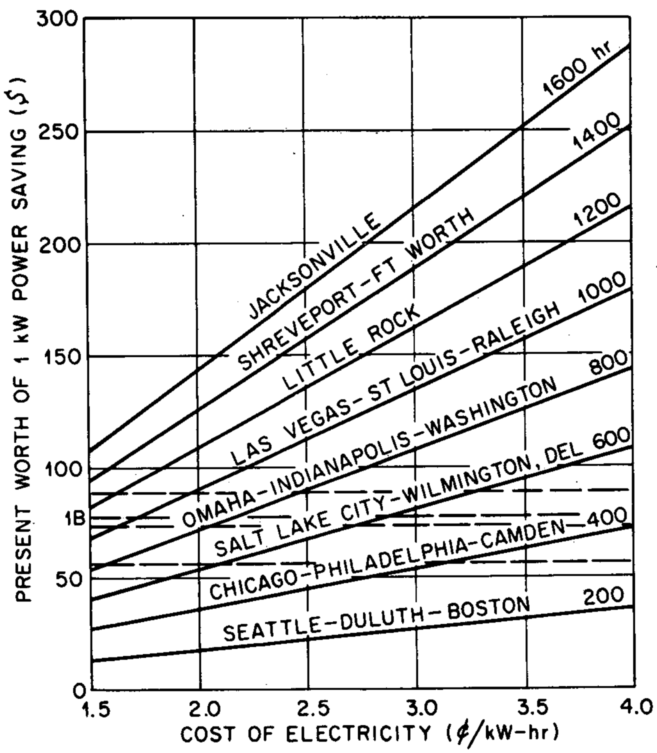
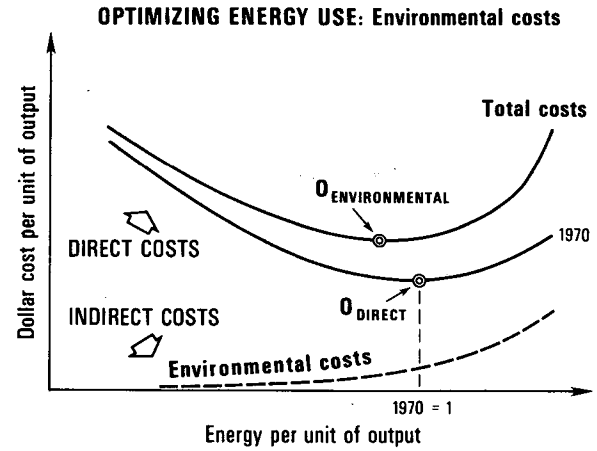


Figure B.2. Present Worth of 1 kW Power Saving as a Function of Annual Hours and Energy Cost (18% Interest Rate — 10 Years).

XBB 744-2407

Figure 16. Present worth of 1-kW power savings as a function of annual hours and energy cost, for selected locations, 18% interest, 10-year amortization. If environmental costs were included, or if electricity was more costly during peak usage periods, consumers would be justified in paying much higher prices for more efficient air conditioners.



Note: Shift of Optimum from O_D to O_E exaggerated to show effect of environmental cost of energy on optimum use.

XBL 759-4099

Figure 17. Optimizing energy use. There are many combinations of energy use and other economic inputs that provide a given output. This figure shows the total cost of that output for different amounts of energy use. The shift of optimum from O_D to O_E is exaggerated to show the effect of the environ mental cost of energy on optimal use. As energy prices rise, the optimum moves toward lower energy use. Even if energy use were economically efficient (based on direct costs), inclusion of environmental costs, which tend to rise nonlinearly with increased energy use, would shift the optimal point of energy use toward slightly lower energy use.

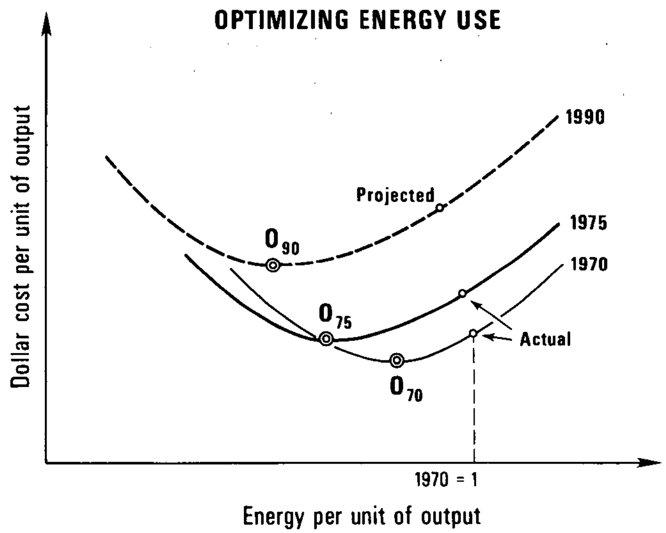


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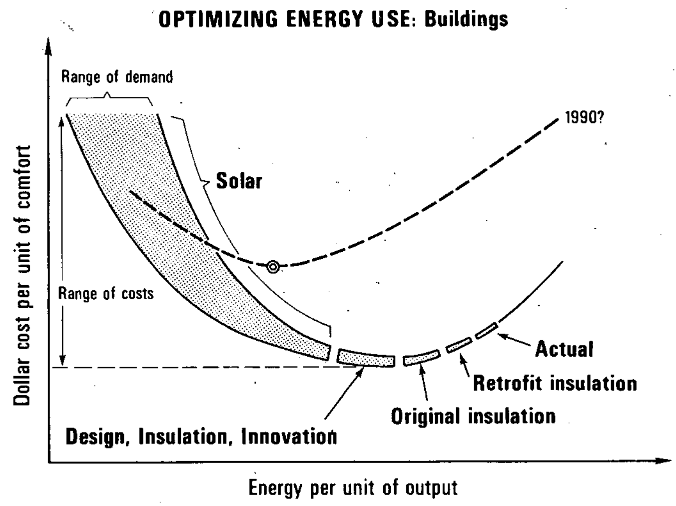
Figure 18. Optimizing energy use. Energy use was economically inefficient in 1970 and 1975, as symbolized by the differences between actual and O (optimal). If historical growth in use persists despite higher energy prices, use will be even more economically inefficient than use in 1975.



XBL 750-4100

Figure 19. Optimizing energy use: buildings. Actual conservation strategies, such as those listed in Tables 9 and 10, can be displayed in curves similar to this one. Solar heating/cooling is not economic in many buildings at 1975 energy prices, but it would become more economic in the future (1990) as energy prices rise. The ranges for cost and energy savings of solar heating/cooling reflect uncertainties as well as the use of nonsolar backup systems. Comfort can be defined by using temperature, humidity, and other physical-physiological parameters.

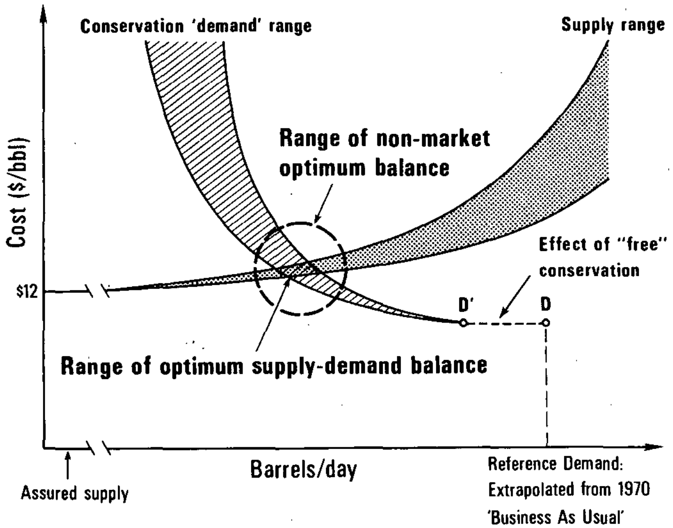


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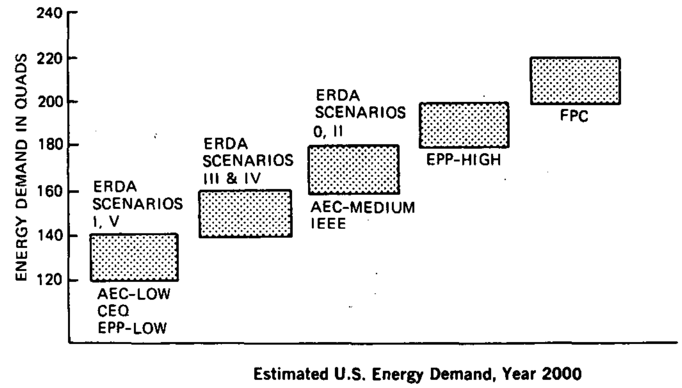
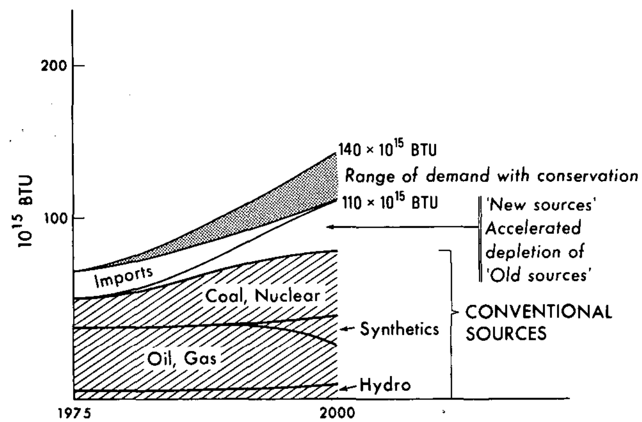
Figure 20. Generalized comparison of future costs of increasing supply and increasing efficiency. Compared with historical extrapolations, demand would be lower through conservation that takes place with immediate cost-savings "free" conservation. Beyond that point other economic factors substitute for energy (as explained in the text) until the cost of saving an additional barrel of oil, or barrel of capacity per day, exceeds the marginal cost of generating one. Because of qualitative and quantitative uncertainties, the optimal supply-demand balance is best represented by the darker shaded area, with the circle indicating the effect of non-market factors on this optimum.



XBL 758-7690

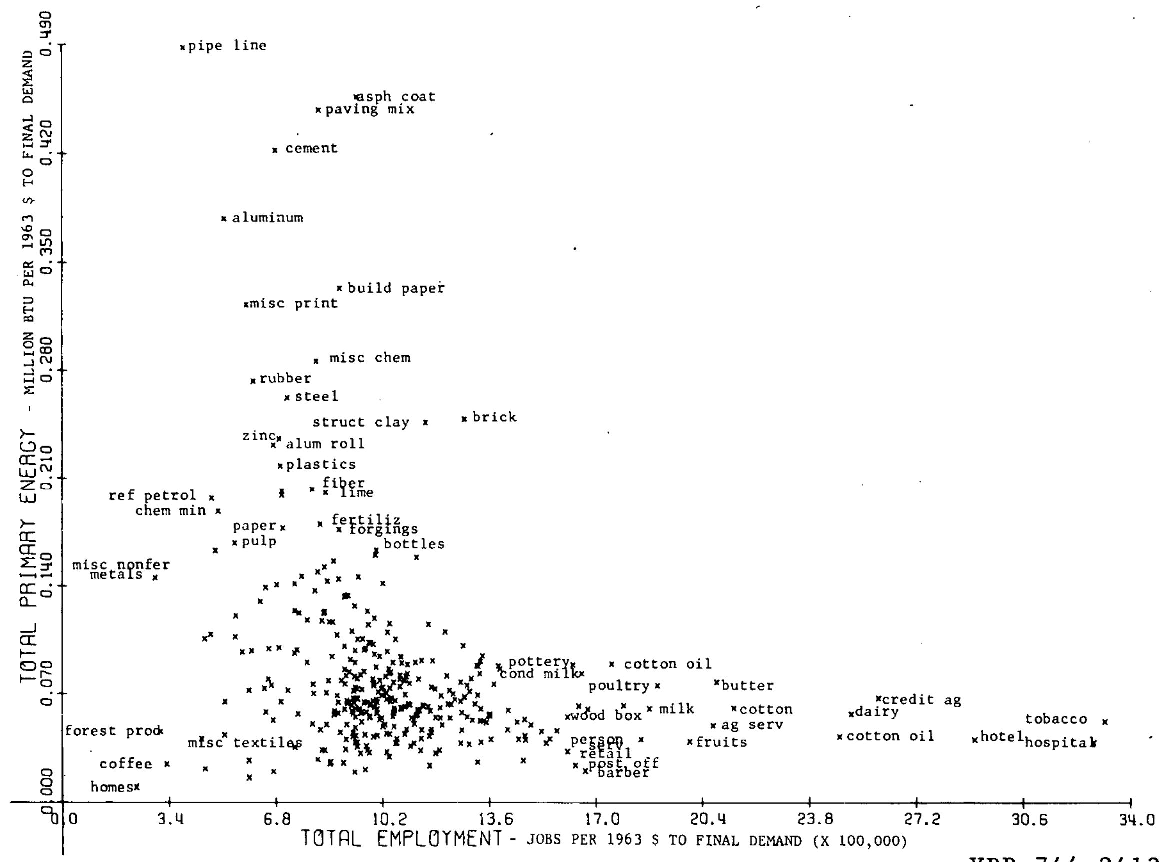
Figure 21. Comparison of forecasts for estimated US energy demand for the year 2000. ERDA scenarios are found in (16), EPP (Energy Policy Project) in (13); others are discussed in (1, 4).



XBL 759-4092

Figure 22. One possible approach to the "low" scenarios of Figure 21. Source: (14).

FIGURE 1. TOTAL (DIRECT AND INDIRECT) ENERGY VS EMPLOYMENT INTENSITIES FOR 362 SECTORS IN 1963.
SOURCE: CAC ENERGY - EMPLOYMENT POLICY MODEL FEBRUARY 1973.



XBB 744-2413

Figure 23. Total direct and indirect energy and labor intensities for 362 economic sectors in 1963. Source: (51). 1971 figures are similar.

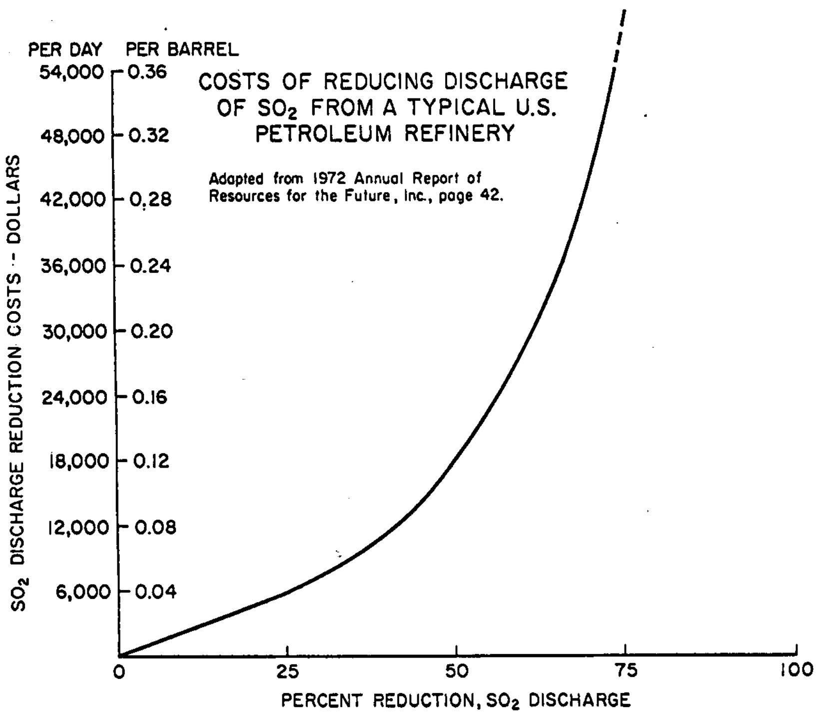


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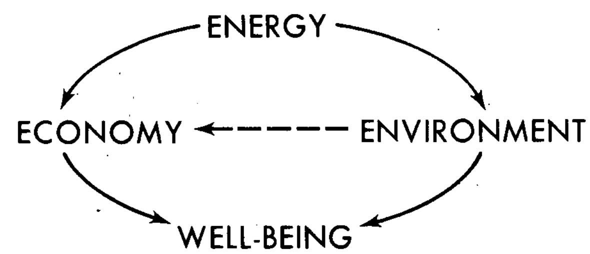
Figure 24. Costs of reducing discharge of SO_2 from a typical US petroleum refinery. Source: (21).



XBL 759-4095

Figure 25. Symbolic representation of the double interaction of energy and well-being. The beneficial use of energy in the economy is partially offset by the adverse impact that energy use has on the environment, affecting well-being directly as well as through the economy itself. Drawing due to J. Holdren, private communication.

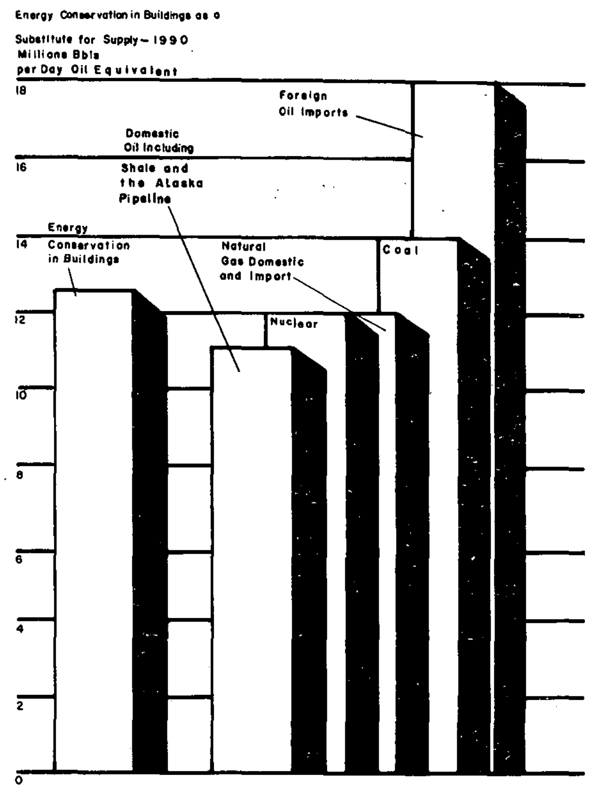


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Figure 26. Comparison of the potential for energy conservation in buildings with some supply options, 1990. Source: (121), with supply options taken from (1).

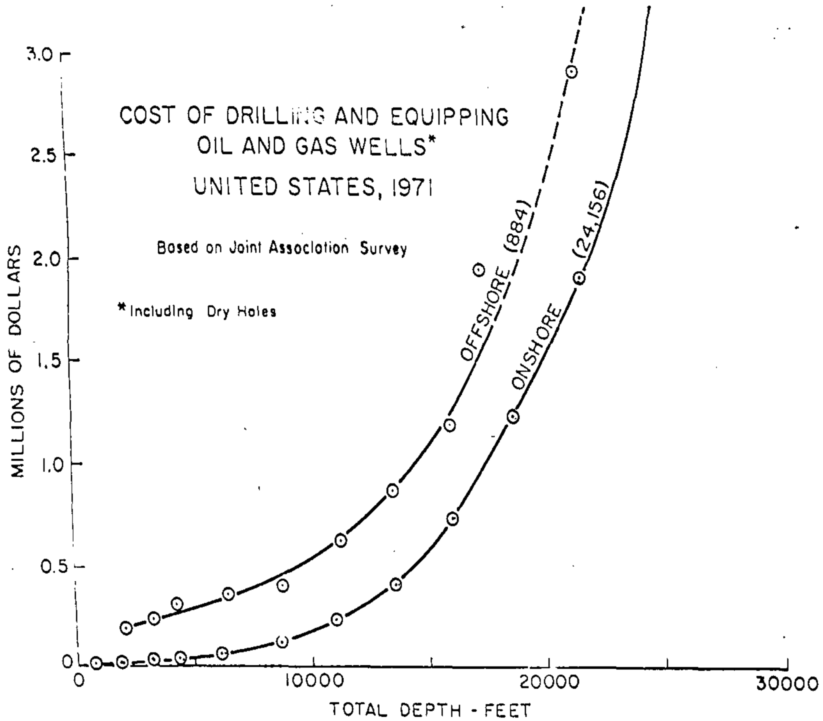

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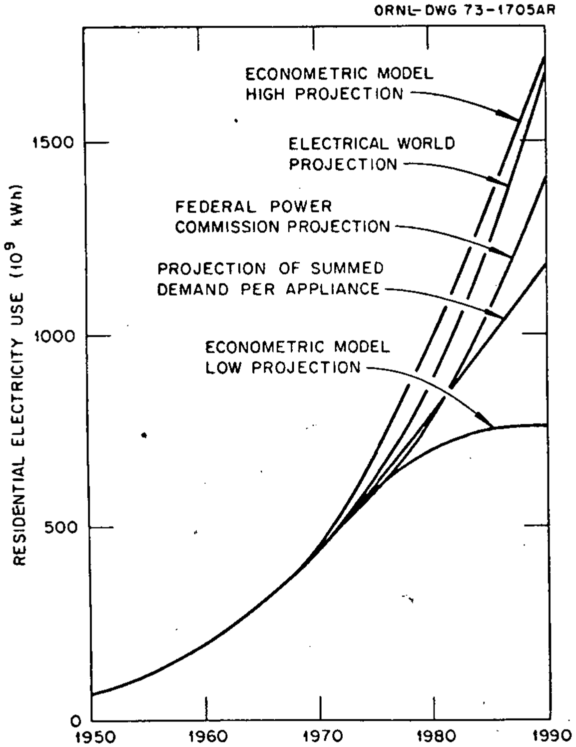
Figure 27. Cost of drilling and equipping oil and gas wells (including dry holes) in the United States, 1971. Source: (21).



XBL 759-8025

Figure 28. Comparison of some econometric projections of residential electricity use. Source: (41).

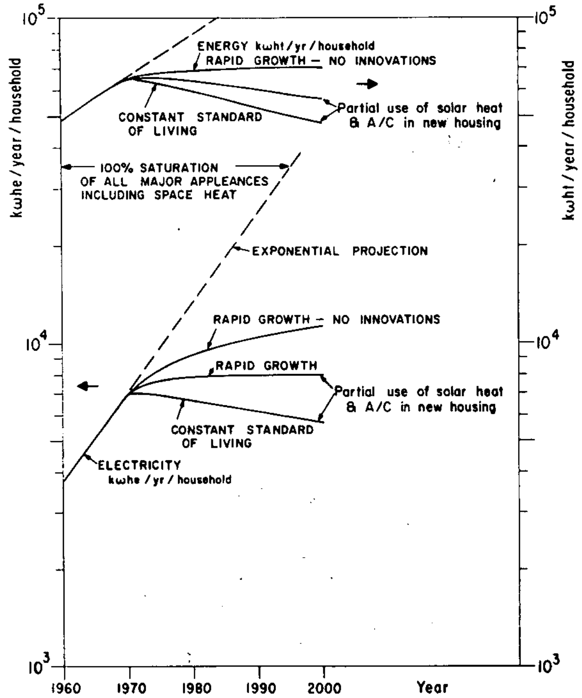


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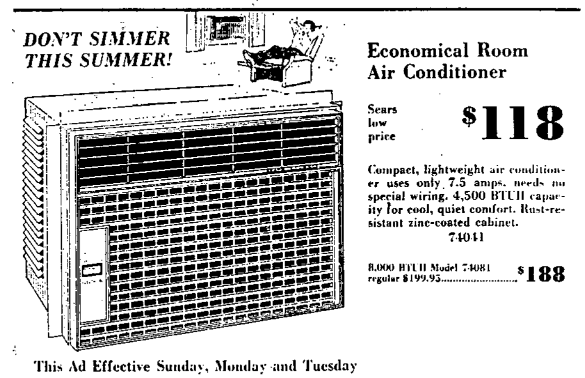
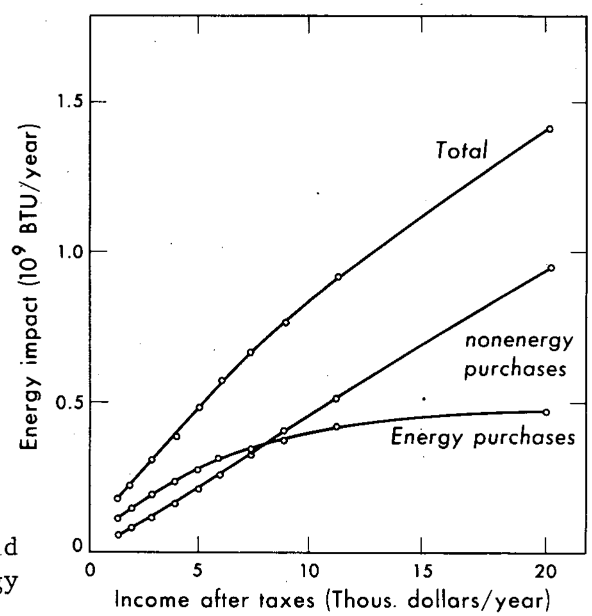
Figure 29. Some projections of residential electricity and energy demand. Higher efficiency and innovations make continued exponential growth (predicted by some models) superfluous. Source: (72).



XBL 757-1758

Figure 30. Advertisement depicting air conditioner with high operating cost and low first cost. A bargain?



XBL 759-4094

Figure 31. Direct and indirect use of energy as a function of household income. Direct means gasoline, heating, electricity; indirect is energy used to provide goods and services. Source (142).

XBB 744-2408

Fig. 32a

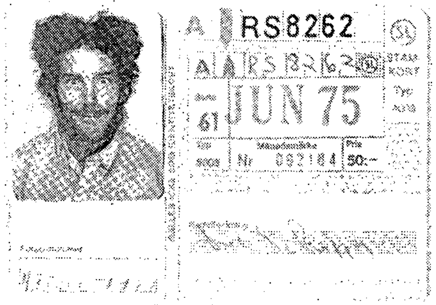


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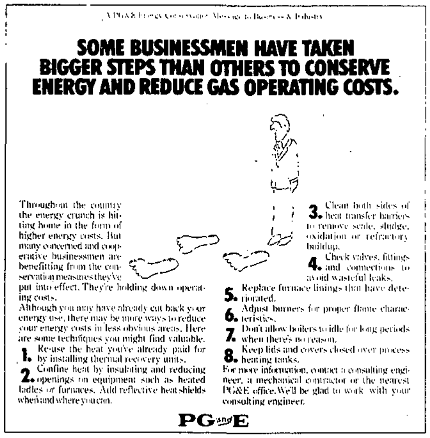
Fig. 32c

CBL 757-5203

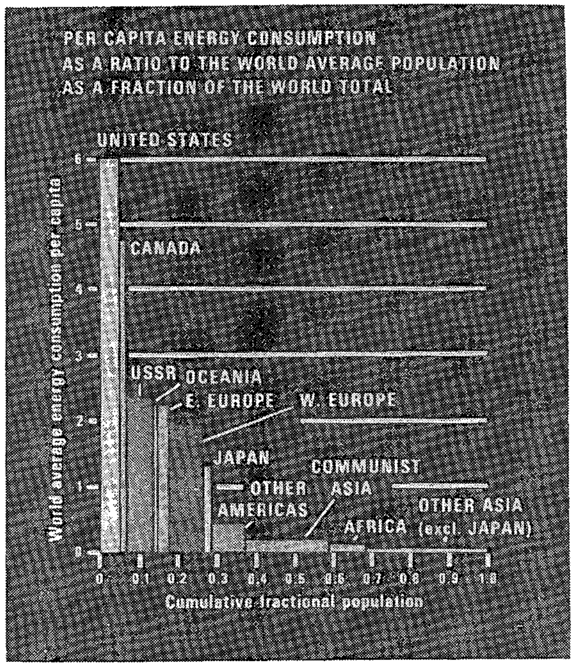
Fig. 32b



XBL 759-8068

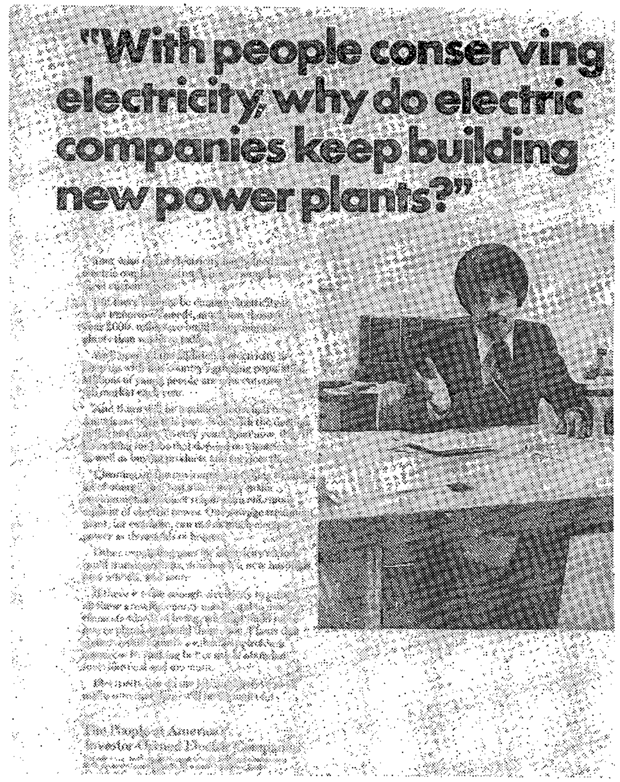
Fig. 32d

Figure 32. Incentives ("carrots") for energy conservation. A: low-interest loans for household improvement. B: rebates for more efficient air conditioners. C: mass transit card from the greater Stockholm "Stockholms Lokaltrafik" mass transit district. (For $17.50/mo. the author was permitted to ride all buses, trains, subways, and many boats in an area the size of the San Francisco Bay Area.) D: direct appeal for higher efficiency--with offer of direct aid from the local utility.



CBB 756-4277

Figure 33. Per capita energy consumption as a ratio to the world average population as a fraction of the world total. Source: International Petroleum Yearbook, 1972 ed.



XBB 754-3189

Figure 34. Advertisement from a group representing many utilities. The advertisement, which appeared in Newsweek in late 1974, expresses the opinion that electricity needs will grow.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720