strategies or goals of a program in progress. The engineering societies also have an advantage over permanent organizations in that they are not responsible for maintaining the employment level or "sales" of such a permanent organization; hence they can recommend program termination when a program is no longer useful.

Engineering societies have responded to requests for help in assembling forums for planning and review; the American Society of Mechanical Engineers, for example, is producing excellent results in developing a plan for R & D in tribology, and the Society of Automotive Engineers is proceeding effectively to plan R & D for road vehicle aerodynamics and tire and suspension rolling losses. Further, effective applied research in any of the technical disciplines requires a community with "critical mass." Planning and review by the engineering societies, as well as interagency coordination, help to assemble such a community, although the effort to make it most effective in furthering applied research should probably be supported by providing support in larger blocks, in one place, over relatively long periods of time.

Conclusions

The critically important role of applied research has been identified in a number of specific past, present, and future activities related to fuel conservation. The importance of applied research generally tends to go unrecognized as compared with basic research and product development processes, not only in fuel conservation activities but in virtually every area of technology implementation. There are well-defined roles for both government and industry in the effective utilization of applied research, and the engineering societies offer a potentially effective existing framework for government and industry to implement these roles.

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U.S. Energy Demand: Some Low Energy Futures

Demand and Conservation Panel of the Committee on Nuclear and Alternative Energy Systems

This article presents several plausible energy demand scenarios for the United States through the year 2010, each one derived from analytic efforts conducted by the Demand and Conservation Panel (*1*) of the National Research Council's Committee on Nuclear and Alternative Energy Systems (CONAES). While the CONAES study (*2*) covers a range of plausible energy futures—from continued rapid growth in demand to actual reductions in demand—we focus here on futures in which demands are lower, in order to provide insight into how energy demand growth can be reduced, and on the consequences of low energy growth. As a further effort to explore low energy growth, we assume future economic growth to be smaller than it has been in the past or than many think it likely to be in the future. This analysis is not intended to show that low demand futures are the most likely or the most desirable; instead, it is meant to illustrate the opportunities for lower energy demand growth and the public policies required to realize these opportunities.

Low energy futures could result from constraints on supplies that appear as higher prices, import restraints, rationing, taxes, or other public policies (for instance, in response to limitations on oil and gas imports, SO_x and CO_2 production, and nuclear power). They could also result from a national decision to use energy resources more efficiently or from shifts in social priorities (such as less pollution of air and water). Adjustments to these changed conditions, whether in developing new energy supplies, expanding old ones, devising a more efficient utilization system, or changing the mix of goods and services demanded, will require decades of effort. To devise and implement a reasonable

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plan of action we must gain a better understanding of future supplies of energy (and their cost) and at the same time project plausible levels of demand for energy, identifying factors that can influence the future course of demand (energy price, population and income growth, status of technology, and so forth).

Summary. The basic features of the U.S. energy supply and utilization system change so slowly that an understanding of the dynamics of major change requires projections that extend several decades. Over such a time most energy-consuming capital stock is replaced, life-styles change, and technology evolves. This study of plausible low energy futures leans heavily on detailed engineering analysis of demand by sector, combined with econometric techniques where appropriate. The results indicate that, given time for the system to respond to prices, regulations, and incentives, U.S. energy demand is very elastic. Consequently, a major slowdown in demand growth can be achieved simultaneously with significant economic growth by substituting technological sophistication for energy consumption.

The scenarios presented here suggest that there is much more flexibility toward reducing energy demand than has been assumed in the past. Indeed, it appears that very similar conditions of habitat, transportation, and other amenities could be provided in the year 2010 with primary energy consumption ranging from 60 to 135 $\times 10^{15}$ Btu's (quads). This wide range of plausible future energy demands results from the technically possible responses to various price and policy possibilities.

Background

For many decades before the 1970's, the price of a unit of energy was a small and steadily decreasing part of almost everyone's budget. Major discoveries of oil and gas, combined with rapidly advancing technology, led to falling energy prices and promoted enormous growth in consumption. Not only did we find ever-increasing uses for energy, but because the relative price was falling there was correspondingly less incentive to be concerned about efficiency of utilization; instead, expansion of production (especially of electricity) was attractive because each new generating unit was more efficient and helped lower the average cost of production. Despite falling energy prices and the consequent lack of concern for conservation, efficiency of energy utilization improved steadily. For example, industry's energy consumption per unit of output fell at a rate of 1 to 1.5 percent per year from 1950 to 1970 (*3*). Indeed, in the past half-century, U.S. energy consumption per capita rose by 50 percent while the productivity of that energy—the ratio of gross national product (GNP) to energy consumed—rose by 70 percent. Part of this improvement came about through conversion from coal to oil and gas (conversion of railroads from coal-fired steam to diesel) but much is attributable to other factors such as new processes and advances in materials (solid state electronics, improved insulation) that made possible more efficient energy conversion and utilization.

Between 1946 and 1973 amenities such as large automobiles, air conditioning, frost-free refrigerators, and home freezers changed from luxuries to necessities and found ready markets. The future, according to many observers, was filled with prospects of ever-cheaper energy that would provide for our many wants, enable resource production from low-grade ores, and turn deserts green with desalted water. Electricity so cheap that it would hardly pay to meter it was even conjectured. Such times of technological Nirvana now seem far more than 15 years in the past.

Several separate events occurred over the past decade that have profoundly influenced both our energy systems and our perception about the future.

- As low-cost domestic oil resources were consumed, the nation began, in the late 1960's, to depend on imported oil, which was then cheap. The hidden costs (vulnerability to cutoffs and discontinuities in price) of that dependence appeared with the oil embargo of 1973.
- Low-cost nuclear power emerged more slowly and turned out to be more costly than anticipated. Costs of other new energy forms (such as synthetic fuels from coal) also escalated rapidly.
- There was increased awareness in the 1960's of external costs of energy production, such as pollution and health and safety costs. External costs contributed to energy price increases in the 1970's as some of them were internalized. Some coal users switched to oil and natural gas, pushing up demand for those rapidly depleting energy forms.

The long-term trend of declining real energy price (that is, corrected for inflation) was reversed in the early 1970's, when major price increases were traumatically introduced by the Organization of the Petroleum Exporting Countries (OPEC) (fall 1973) and other fuel prices subsequently moved upward (Fig. 1). The trend toward higher prices is not likely to be reversed soon. At issue, therefore, is the extent to which society can respond to these higher prices not by sacrifice but through conservation—substitution of activities and increased efficiency of use.

What Is Energy Conservation?

Few concepts are subject to as many different interpretations as energy conservation (*4, 5*). In recent years, most people have associated conservation almost exclusively with curtailment, as unanticipated interruptions in supplies of oil and natural gas have forced Americans to cut back on energy use. In this article we do not view conservation as curtailment. Instead, conservation includes technological and procedural changes that allow us to reduce demand for energy (or specific scarce fuels) without corresponding reductions in the goods and services we enjoy. That is, conservation is a means of enhancing the energy user's perceived welfare; it leaves society materially better off than it would be otherwise and therefore is an act of enlightened self-interest; it implies that benefits of conservation actions exceed costs. These changes can be accomplished by substituting capital (insulation) or ingenuity (new microprocessor controls on heating systems) for the brute force use of energy to accomplish a particular task. Our definition allows for changes in the market basket of goods and services making up the GNP, as consumers shift to less energy-intensive goods and services to meet their needs (shifting to less energy-intensive modes of travel, buying more durable or repairable goods).

In the United States today the need for economic efficiency alone demands that energy be conserved. Energy is being wasted in buildings and industrial processes because they were designed in an era when today's energy scarcities and price levels were not foreseen; the energy component of operating costs was then too small to warrant much attention. Today we find it cost-effective to upgrade much energy-consuming equipment and to build more energy-efficient vehicles, industrial equipment, and buildings for the future. In the past, government policies led to energy prices far below replacement cost—the price level that would occur under perfect market conditions. As these policies are changed, higher levels of energy conservation will become economic.

Many advocates argue for more energy conservation than even "perfect" market signals would call for. The most commonly cited reason is that we should reduce oil imports to minimize our vulnerability to embargoes and our balance-of-payments deficits. Some of the other reasons have to do with timing; President Carter maintains that energy conservation can give us time to reevaluate our commitment to the plutonium breeder reactor and possibly achieve a significant reduction in the risks of nuclear proliferation. Holdren (*6*) and Lovins (*7*) suggest that too much energy too soon may create greater hazards than too little too late and recommend energy conservation policies. Conservation would provide the nation with the flexibility to pick and choose among long-term energy options as the uncertainties surrounding nuclear waste management, the technology of solar cells, and the climatic effects of fossil fuel combustion are clarified. Kissinger (*8*) points to the possibility that oil exporting nations may accumulate balance-of-payments surpluses large enough to precipitate financial crises and economic chaos in the industrial democracies of the world. Other reasons for conserving energy are based on ethical considerations such as the fact that the United States has only 5 percent of the world's population, yet consumes more than one-third of the world's energy, and the belief held by environmentalists that major external costs remain in the energy system and that much of our finite energy resources should be saved for future generations.

The Demand Study

In this study the Demand and Conservation Panel examined some plausible paths that energy demand might take in the future (through 2010) in response to price and other factors. It was undertaken in support of a more comprehensive CONAES study of the future of energy supply and demand (*2, 9*). Panel members were chosen to provide a diversity of points of view and disciplinary skills. Additional resources and expertise were brought into the study by several resource groups, which were formed by the Panel to examine specific issues (*1*).

At the outset, the Panel encountered considerable conventional wisdom about energy use that has found extensive, if tacit, acceptance in various segments of American society. The following are some examples of what are now known to be misconceptions about energy use.

- Energy and the production of goods and services are intimately and inextricably linked: energy is a relatively fixed factor in GNP.
- Energy consumption and jobs are inextricably tied together; more energy consumption means more jobs, and vice versa.
- Higher illumination levels generally help productivity; low illumination is injurious to the eyes.
- Reducing the growth of energy consumption implies replacement of machines (bulldozers) with manual labor (men and women wielding picks and shovels).
- Turning down the thermostat at night is counterproductive; the energy used in heating up the house in the morning more than offsets any savings.

This kind of folklore indicated a need to develop a more quantitative technical and economic understanding of the dynamics of energy consumption. The Panel decided to map out a broad range of plausible future levels of consumption (*10*). Since consumption is influenced by many factors, certain things were assumed, such as population growth rate at Census Bureau series II, and others were allowed to vary, notably the price of energy, the economic growth rate, and public policies.

Economic growth was assumed to vary linearly in time, with total (real) GNP doubling by 2010. In a variant analysis GNP was allowed to triple by 2010. The latter case corresponds to an average real GNP growth of 3 percent per year between 1975 and 2010 with higher than average growth in the near term (for example, 4 percent) and lower growth in the long term, reflecting lower population growth. In this article we report results based on the assumption of a 2 percent average growth rate, again with higher than average growth in the near term. It should be emphasized that even in these low-demand futures we assume a doubling of real income over the next 35 years.

For most scenarios, price was used as the primary driving force behind the different outcomes. There were three pricing assumptions, corresponding approximately to prices four times, double, and equivalent to 1975 prices (see Table 1). A very low growth variant, assuming significant changes in life-style, was also studied.

Prices serve many functions in a market economy. They reflect the relative scarcity of resources and serve as signals to producers and consumers in allocating the supply of and demand for energy resources. Prices assumed for the scenarios were allowed to reflect external costs as they affect occupational and public health as well as environmental quality, and the degree to which these costs become internalized in the costs of energy products.

Public policies can serve these functions as well. First, they can and do affect price. Environmental regulations internalize costs, tax policy affects pricing patterns, and regulatory agencies (such as state utility commissions) sometimes set prices. For example, in response to external costs, regulation has set minimum standards on car safety, air pollution, pesticides, strip-mining, and mine safety. Second, conservation education can shift the mix of goods and services demanded as well as their energy efficiency. Third, tax subsidies can and have promoted production. Therefore

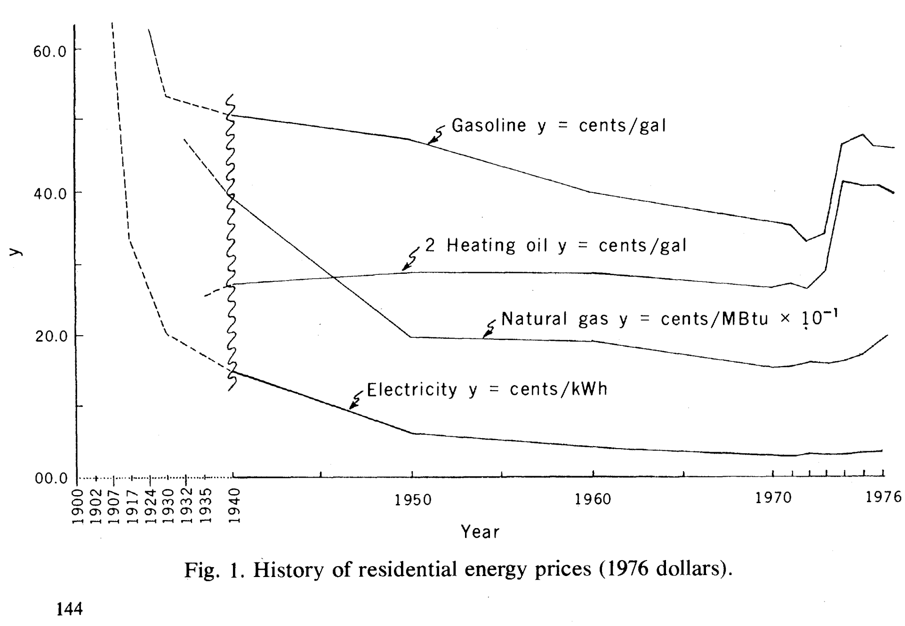

Fig. 1. History of residential energy prices (1976 dollars).

public policies can be alternatives or surrogates for price changes, seeking to reflect social value and cost and guide producers and consumers in decisions concerning production and consumption.

In analyzing the dynamics of demand over such an extended period of time it was decided to invoke several different techniques.

1) *Near future (the next decade).* Since energy consumption patterns in this period will strongly reflect the characteristics of existing capital stock, the most appropriate approach was felt to be econometric analysis. In applying this technique, recent trends in energy consumption were analyzed and used to project demand as influenced by both price and nonprice factors. Statistical techniques were used to determine the past quantitative relationships of energy use to energy prices, conservation efforts, incomes, GNP, population, and other demographic and economic factors. Energy demand in the future was defined by the interaction of these observed historical relationships tempered by the assumptions of future economic and demographic variables. Although this technique can be used to examine historical variations in energy use in relation to geographic variations in energy prices and income to obtain near-term insights, it has limited validity for application to the distant future. It cannot logically be applied to periods with major differences in economic structure or energy prices. The contribution of econometrics to the work of the Panel was that it indicated whether the short-term response to assumed prices and incomes in each scenario leads energy demand to follow a path in the near future that is consistent with the Panel's energy projections into the next century.

2) *Longer-term future (to 2010).* Energy consumption characteristics of various amenities (such as transportation and habitat) can change markedly over periods comparable to the average lifetime of energy-consuming capital equipment (cars, air conditioners, and houses). Social conditions and attitudes can also change greatly over a 35-year span. Therefore, even though our analysis will undoubtedly turn out to be somewhat off the mark, it is important because actions taken today will significantly affect the conditions that exist in 2010. A detailed engineering approach was taken to analyze plausible energy trends in each consuming sector over the long term. Energy consumption was partitioned into three sectors—residential and commercial buildings and appliances, industry, and transportation—which were examined independently. The results of the independent sectoral demand analyses were integrated, using energy input-output analysis to make them consistent with a specified market basket of goods and services making up the GNP in each scenario.

Table 1. Detailed price schedules for key fuel types were determined for each scenario. Average consumer prices for distillate oil, natural gas, utility coal, and electricity in 2010 are given in 1975 dollars per million Btu's. Prices are assumed to change slowly and continuously between 1975 and 2010.

Scenario	Consumer price ($/MBtu)			
	Distillate oil	Natural gas	Utility coal	Electricity
	1975			
Actual	2.81	1.29	0.81	7.91
	2010			
I and II	13.49	14.84	3.24	26.37
III	6.74	7.42	1.62	15.82
IV	2.81	3.09	0.81	7.91

For the scenarios presented here, the real GNP growth rate was assumed to slowly decline from 3 percent in the late 1970's to about 1 percent in 2010, corresponding to a linear increase and a doubling of real GNP over the 35-year period. The reduced GNP growth rates in the latter years stem from expected reductions in the rate of growth of population and the labor force. The assumption that GNP will rise while the labor force is leveling off implies a positive rate of growth in productivity, but does not specify the sectors in which it occurs. The scenarios may be taken to reflect various assumptions about relative price changes in energy and nonenergy sectors, or price may be considered simply a surrogate for a variety of government policy options.

All scenarios implicitly account for the development and market penetration of new technologies and products. This is accomplished by specifying the market basket of consumer goods and services consistent with a fixed GNP. Any new product within this limit would have to displace another; only the differential energy requirement would be relevant.

Caveats. Neils Bohr pointed out that "it is very difficult to make an accurate prediction, especially about the future." We feel that for such subjects as energy demand it is even very difficult to make an accurate projection. Thus, we present our major disclaimers about the study.

• It is assumed that the future unfolds smoothly. Energy prices are a primary driving force behind the analyses, and it is assumed that they are known to energy users or that appropriate regulations compensate for the lack of perfect information. If there is extreme uncertainty about energy prices, and reason to believe that they may drop significantly, many persons will choose not to make major capital investments in conserving technologies.

• For most of the outcomes studied it is assumed that personal tastes will not change very much from those of today. Roughly the same (albeit twice as large) market basket of goods is to be provided to consumers in 2010 as today. Changes

Table 2. Energy demand scenarios.

Scenario	Energy price ratio, 2010/1975*	Energy conservation policy	Energy in 2010 (quads)					
			Buildings	Industry	Transport	Total	Losses†	Primary consumption‡
I	4	Very aggressive, deliberately arrived at reduced demand requiring some life-style changes	6	26	10	42	16	58
II	4	Aggressive; aimed at maximum efficiency plus minor life-style changes	10	28	14	52	22	74
III	2	Slowly incorporates more measures to increase efficiency	13	33	20	66	28	94
IV	1	Unchanged from present policies	20	39	26	85	51	136
1975			16	21	17	54	17	71

*Overall average; assumptions by specific fuel type were made reflecting parity and supply; price increases were assumed to occur linearly over time. The price was assumed to be either that actually charged at the final point of demand or the shadow price reflecting a policy. †Losses include those due to extraction, refining, conversion, transmission, and distribution. Electricity is converted at 10,500 Btu/kWh, coal is converted to synthetic liquids and gases at 68 percent efficiency. ‡These totals include only marketed energy. Active solar systems provide additional energy to the buildings and industrial sectors in each scenario. Total energy consumption values are 63, 77, 96, and 137 quads in scenarios I, II, III, and IV, respectively.

Table 3. Total primary energy consumption in 2010 by fuel type. Each set of numbers represents only one of a wide variety of energy resources that could be used to meet energy demands. Because energy resources are largely interchangeable over the long run, the actual mix in 2010 can be influenced by changes in price, technology, and policy.

Fuel type	Total primary energy consumption (quads)				
	Scenario				1975
	I	II	III	IV	
Liquid fuels*	24	29	38	50	30
Gaseous fuels†	8	9	11	26	17
Coal (direct use)‡	10	11	13	10	4
Electric inputs§	17	26	32	50	26
Total purchased fuels‖	58	74	94	136	71
Active solar¶	5	3	2	1	Negligible
Totals	63	77	96	137	71

*Liquid fuels include petroleum, shale oil, and synthetic liquids derived from coal. †Gaseous fuels include natural gas and gasified coal. ‡Figures do not include coal used for liquid and gaseous fuels (necessary in most of the scenarios) or for electricity production. §Includes coal, nuclear, hydro, geothermal, and oil (for peak demand only). ‖Because of rounding off, totals may not equal the sums for fuel sectors. ¶Estimated use of active solar units in buildings and industry.

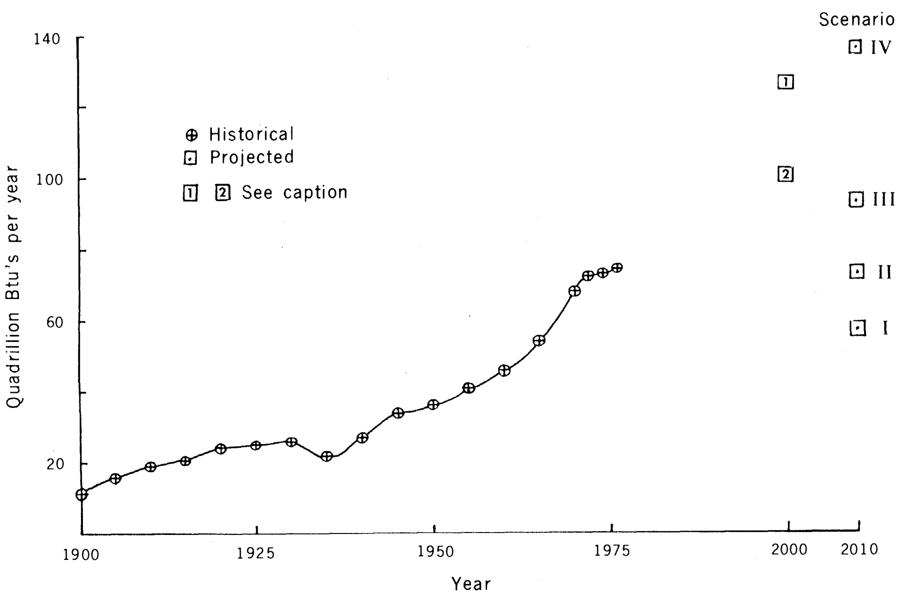

Fig. 2. Summary of total U.S. energy demand scenarios. Some information was obtained on values for 1990, but the detailed evaluations were focused on 2010. Other results shown for comparison are $\boxed{1}$ the Energy Policy Project (EPP) (*16*) "tech fix" case and the Institute for Energy Analysis (IEA) (*18*) "high" case, and $\boxed{2}$ the EPP "zero energy growth" case and the IEA "low" case.

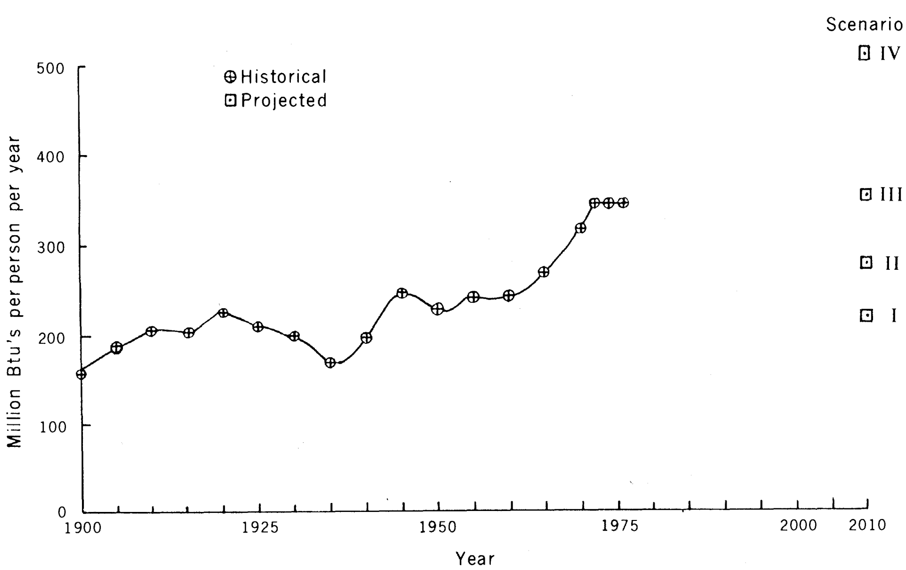

Fig. 3. Per capita energy demand history and projections. Population growth rate was assumed to be that given by Census Bureau series II.

in values could modify this assumption drastically.

• Because the use of energy in the United States is so inefficient, energy consumed in providing an amenity can be reduced by changes in efficiency over a relatively wide range (*11, 12*). That is, an increase in the real price of energy can make it economically very attractive to use less energy to provide a particular amenity. Recent history shows that the effect of price can just as easily be produced by regulation, standards, incentives, and disincentives; it can also be produced by supply uncertainty, especially in the industrial sector.

• Long-term economic growth is exceedingly difficult to predict because it depends on vagaries of population growth, politics, social attitudes, labor productivity, technological innovation, and resource availability. Therefore any long-term GNP or, for that matter, population assumption is subject to challenge.

• Almost all of our past experience with energy (the basis for econometrically derived price elasticities) has been in an era of falling real energy prices. The lag times associated with price elasticities may not be applicable under conditions of rising real prices.

• Energy consumption models that are primarily based on engineering can only be approximate; this is partly because assumptions must be made about economically rational market behavior. For example, people may choose to buy a slightly cheaper, low-efficiency refrigerator and pay higher operating costs.

• New kinds of unusually energy-intensive consumer goods are not assumed explicitly but neither are new kinds of energy-saving technologies. Either or both could change demand patterns significantly in a decade.

• Energy prices are assumed to reach parity—that is, price is assumed to reflect the quality of energy—by the middle 1980's. (This means that coal will continue to be priced lower than oil or gas on a Btu basis.)

Results of the Analyses

Results are presented here for four demand growth scenarios. Each is believed to represent an internally consistent picture of the U.S. economic system in the year 2010. No scenario is presumed to be more probable than the others. They represent a broad range of plausible alternative futures, within the focus of this article on lower-demand futures.

The characteristics of the scenarios are summarized in Table 2. The scenarios highlight the strikingly wide range of energy efficiencies that appear to be technically and economically feasible for a particular level of economic activity. The energy demand paths are illustrated in Fig. 2. The demand levels in 2010 were obtained by using input-output synthesis of the separate sectoral analyses. Trends and projections in terms of per capita energy demand are shown in Fig. 3 and the energy GNP ratio in Fig. 4.

Plausible energy supply mixes corresponding to the scenarios are summarized in Table 3. However, it must be remembered that over a period of decades the mix of fuels (as well as aggregate demand) can change considerably. A discussion of the amount of electricity that could be used is given later in this article. The energy supply mixes shown in Table 3 are quite conventional: resource conservation significantly reduces the imperative for crash programs to develop new technologies and provides the flexibility to eliminate one or more technologies for environmental or safety reasons.

In scenario I we examine a set of fairly extreme changes by considering the combined implications of substantially higher energy prices, significant life-style accommodations, and reduction of energy consumption by equipment to approximately 60 percent of the per capita level today. Some shift of the population to warmer climates and colocation of industry and residences is assumed. For the intermediate scenarios (II and III), we assume substantially higher energy prices and corresponding major market accommodations to obtain amenities less expensively. The results for scenario II indicate the extent to which a society that chooses a high efficiency of utilization, through technical sophistication and innovation of its social institutions, can avoid substantially modifying the nominal market basket of goods and services. The results obtained for scenarios III and IV reflect a future much like today, where efficiency improvements in familiar energy-consuming devices permit production of goods and services with corresponding changes in life-styles. It should be noted, however, that even though the assumed efficiency improvements are cost-effective in terms of assumed energy prices, they are not likely to be achieved in the absence of supportive policies.

Econometric results. Long-run price elasticities were found to be comparable to those reported in other recent studies (*13*). The greatest response observed was the long-run price elasticity of -1.7 (industrial use of natural gas), while the smallest was the elasticity of -0.4 for gasoline use with respect to gasoline price. Historic price responses provide a basis for examining how near-future growth in energy demand may vary with energy price.

Differentiation of conservation, price, and income influences in reducing energy demand in 1974 showed that after the increase in energy prices and the decline in personal incomes throughout the country were taken into account, energy use fell below what would be expected from this price- and recession-induced decline. This nonprice-induced conservation effect accounted for further reductions in use of 6 percent (residential-commercial electricity) to 13 percent (industrial use of coal). It probably reflected lower speed limits, increased energy awareness, and simple improvements in energy management. It is impossible to know whether this nonprice effect will continue in the future; however, it apparently existed in a weaker form in 1975, and essentially disappeared in 1976. One such projection (for scenario III) is reproduced in Fig. 5. It shows the near-future econometric forecast associated with twofold growth in real energy prices from 1975 to 2010.

Opportunities for improved efficiency

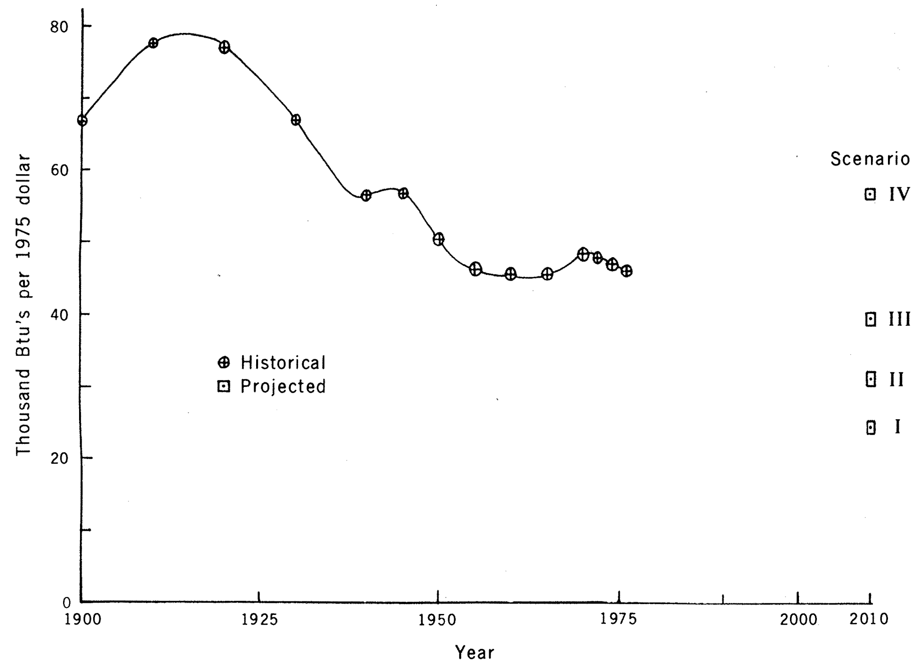

Fig. 4. Time dependence of the energy/GNP ratio. Many factors such as market basket choices and the price of energy can affect this ratio. Long-term trends in the ratio reflect changes in technology as they affect the energy intensity of new capital stock.

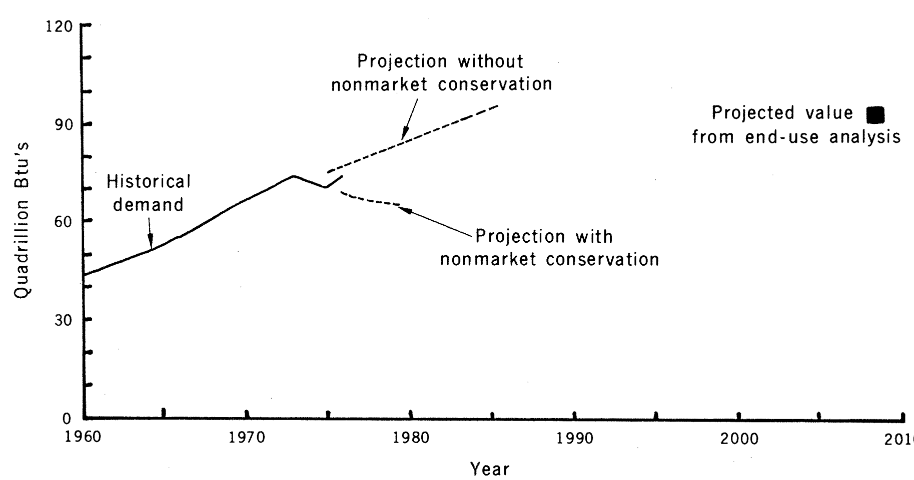

Fig. 5. Energy demand projection for the next 10 years. This example, corresponding to scenario III, indicates the range of total U.S. energy demand that could occur. The upper dashed line corresponds to demand driven by price factors, the lower one to demand influenced by price factors as well as nonmarket factors, including heightened awareness and regulations similar to those existing in 1974 and 1975. The demand value in 2010 obtained through detailed end-use analysis is consistent with extension of the range of econometrically derived demand.

of use. Analyses of the engineering potential for higher efficiency show that major opportunities exist in all sectors of demand and that the economic incentive to shift to higher efficiency is a strong function of the price of energy. Figures 6, 7, and 8 illustrate this point (*10, 14, 15*). Although the most impressive opportunities for higher efficiency of use occur with *new* capital goods, there are also many good ways to improve the efficiency of the existing system (operation of buildings, industrial processes).

Highlights of the Scenarios

Scenario IV. With the exception of the price of natural gas (which more than doubles by 2010), energy prices remain constant in this scenario over the entire period, possibly because of breakthroughs in the supply sector or public policies that provide subsidies to energy price. Higher gas prices might result from either deregulation of wellhead prices, regulation at increased price levels, or the introduction of synthetic gas produced from coal.

Despite the lack of higher energy prices, the incentive to increase efficiency of use is greater than it was before 1972, because in those years real energy prices were falling. Furthermore, energy prices are higher today than they were when most existing capital investments were made. Therefore there are additional incentives to increase efficiency even without further improvements in the technology of energy utilization. As a consequence, the efficiency of energy use improves modestly over the period. Representative changes are given in Table 4.

In the buildings sector, the lagged effect of postembargo energy prices and public policy actions already under way result in efficiency improvements in new stocks through 1980. Because of continued increases in gas prices, small improvements in most gas appliances occur beyond 1980. The better performance in new products and buildings is felt throughout the period to 2010 as older stocks are replaced. However, improvements occur very slowly; for example, electric space heating continues to be dominated by resistance heaters. In the industrial sector the historic trend to lower energy consumption per unit output continues but at a slower pace, resulting in an overall drop of 18 percent by 2010.

In transportation, per capita energy consumption grows modestly, but technological advances result in small improvements in efficiency. Current policies [such as miles per gallon (MPG) standards for automobiles] continue. No significant shifts occur in freight modes, but the percent of consumer transportation expenditures in air travel increases as automobile travel begins to be saturated (ownership, minutes traveled per day, and so on). Transportation energy intensiveness drops in all sectors. Mass transit travel (per capita) nearly doubles.

Scenario III. In this scenario real energy prices steadily climb, ending in 2010 at twice the 1975 levels. These increases are mostly due to higher production costs as cheap supplies of fossil fuels are exhausted. There are substantial efficiency increases in the buildings, including improvements in thermal integrity of structures and increased efficiency of appliances (see Table 5). Overall building energy use *decreases* at an average annual rate of 0.6 percent, compared to growth of 3 percent per year from 1950 to 1975. The major reason for the decrease in growth rate is the reduction in space heating requirements. Because of differences in assumed energy prices, the relative market share of electricity increases from 21 to 51 percent, while the natural gas share declines from 53 to 21 percent. Electric heat pumps become more efficient and find widespread use. Solar energy becomes increasingly important toward the end of the period for air conditioning, space heating, and water heating. The energy efficiency ratio of new air conditioners in 2010 is close to 10 Btu's per watt-hour (compared with 6 Btu/W-hour in 1975). Because of the increase in energy prices, there are increased expenditures for energy in buildings. However, the percentage of personal income spent for household fuel increases only moderately, from 3.1 in 1975 to 4.3 in 2010. There is a corresponding increase of 3 percent in capital expenditures for buildings and appliances during the period. The technologies to produce the higher efficiencies in this scenario are either currently on the market or are achievable by well-known means. Figures 6 and 7 indicate the kinds of improvements that

Table 4. Energy efficiencies in 2010, according to scenario IV.

Buildings and appliances		Industry		Transportation	
Type	Intensity*	Type	Intensity†	Type	Intensity‡
Thermal integrity (heating)		Agriculture	0.95	Automobile	20 mpg
Residential	0.76	Aluminum	0.79	Light trucks and vans	16 mpg
Commercial	0.7	Cement	0.75	Air passenger	0.5
Government and education	0.5	Chemicals	0.84§	Truck freight	0.9
Space conditioning		Construction	0.73	Air freight	0.6
Air conditioning	0.94	Food	0.86	Rail freight	1.0
Electric heating	0.9	Glass	0.82		
Gas and oil heating	0.8	Iron and steel	0.83		
Refrigeration and freezing	0.92	Paper	0.76		
Lighting	0.70	Other industry	0.85		

*Energy intensity of new construction and products in 2010 compared with 1975. †Average energy per unit production in 2010 compared with 1975. ‡When figures are not given in designated units they refer to energy intensity in 2010 compared with 1975 (including changes in load factor). §Excluding feedstock.

Table 5. Energy efficiencies in 2010, according to scenario III.

Buildings and appliances		Industry		Transportation	
Type	Intensity*	Type	Intensity†	Type	Intensity‡
Thermal integrity (heating)		Agriculture	0.85	Automobile	27 mpg
Residential	0.63	Aluminum	0.63	Light trucks and vans	21 mpg
Commerical	0.6	Cement	0.63	Air passenger	0.45
Government and education	0.45	Chemicals	0.78§	Truck freight	0.8
Space conditioning		Construction	0.65	Air freight	0.6
Air conditioning	0.75	Food	0.76	Rail freight	0.97
Electric heating	0.63	Glass	0.76		
Gas and oil heating	0.75	Iron and steel	0.76		
Refrigeration and freezing	0.68	Paper	0.71		
Lighting	0.70	Other industry	0.75		

*Energy intensity of new construction and products in 2010 compared with 1975. †Average energy per unit production in 2010 compared with 1975. ‡When figures are not given in designated units they refer to energy intensity in 2010 compared with 1975 (including changes in load factor). §Excluding feedstock.

might be expected in the energy efficiencies of structures and appliances. Similar improvements are likely for other kinds of appliances and buildings.

In the industrial sector the steadily increasing price of energy results in slower production growth in the energy-intensive aluminum and chemicals industries than in industries producing less energy-intensive substitutes. The overall weighted average energy consumed per unit output in 2010 is 26 percent lower than in 1975. Some shifts have occurred between producing sectors (less steel, more aluminum and fiber glass), reflecting changed demands by manufacturers and the construction industry. Industrial cogeneration becomes widely practiced.

In the transportation sector, per capita energy consumption in 2010 remains about the same as in 1975 despite slightly expanded passenger and freight movement. The average energy intensity of automobiles (Btu's per vehicle mile) drops to half of the 1975 value, reflecting large gains in automobile performance (Fig. 8). Airline travel grows at an average 2 percent per year. Mass transit use in 2010 (passenger miles per capita) is 3.5 times that in 1975. Although water freight stays relatively constant, rail freight expands (in ton-miles per capita) by about 30 percent and truck freight by

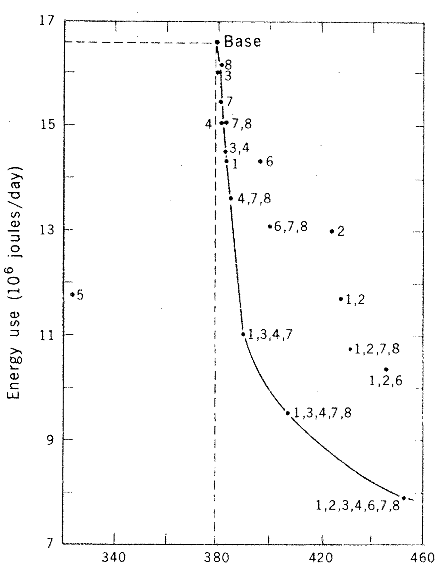

Fig. 6. Energy intensiveness of a typical household refrigerator-freezer combination, plotted against purchase price. The energy intensiveness falls rapidly for relatively small increments in first cost (*14*). Modifications corresponding to the numbered points were: 1, increase insulation thickness; 2, improve insulation thermal conductivity; 3, remove fan from cooled area; 4, add antisweat heater switch; 5, eliminate frost-free and forced air systems; 6, improve compressor efficiency; 7, increase condenser surface area; and 8, increase evaporator surface area.

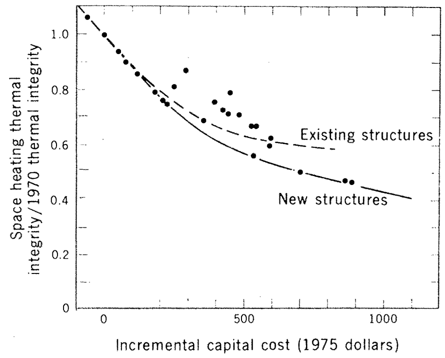

Fig. 7. Energy intensiveness of new and existing residential dwellings as a function of investment in construction (or retrofit). Energy intensiveness falls rapidly for small increases. There are more cost-effective opportunities for new structures because insulation investments cut the required size (and therefore cost) of heating and cooling systems (*15*).

40 percent, and air freight expands threefold.

Scenario II. In this case consumption in 2010 is about the same as today, after going through a peak around 1990. Energy prices increase substantially for all energy forms over the 35-year period from 1975 to 2010. Real energy prices are assumed to essentially quadruple by 2010. Public policies provide incentives, taxes, standards and regulations, vigorous research and development (R & D), and public education to help accelerate the United States toward high efficiency of energy utilization.

Because of the higher prices, there are substantial improvements in new appliances, and buildings are carefully designed and constructed for efficient energy use (Table 6). More energy improvements are made in existing buildings than in scenarios III and IV. As a result, overall energy use in buildings declines from 16 quads in 1975 to 11 quads in 2010. Although energy consumption is reduced somewhat, the very high energy prices result in substantial increases in expenditures for fuel. However, increases in income over the period reduce the relative impacts so that residential fuel expenditures increase only from 3.1 to 4.9 percent of personal income. Thermostats are set back and room temperatures are kept lower in winter (68°F) and higher in summer (75°F). Some new appliance technologies are introduced in this scenario. For example, high-efficiency electric and gas heat pumps may be developed and widely adopted with thermal storage (the annual cycle energy system, where heat is stored in water). Decentralized uses of solar energy for space heating, air conditioning, and water heating make a substantial contribution near the end of the period (25 percent of new air conditioners, 50 percent of new space heaters, and 70 percent of new water heaters in 2010). Improved retrofit measures and construction practices are an important aspect of the scenario. Retrofit measures include extensive insulation of previously uninsulated exterior walls. Passive solar house construction, consisting of heavily insulated structures with a large area of windows facing south, become popular after 1990. Typical house construction would include double 2 by 4 inch exterior walls with a full 8 inches of insulation and 12 inches of insulation in ceilings. Some underground or earth-covered construction would further reduce the energy consumption.

Industry responds to the price trends and tight government regulations and makes large investments in both retrofit and new process development, resulting in an overall decrease in energy consumed per unit output that reaches a value 34 percent lower in 2010 than in 1975. However, the cost of conversion to new, more efficient processes still does not warrant a significantly accelerated write-off of existing plants purely for energy reasons. To achieve this improved efficiency current air pollution standards are not tightened. Throwaway packaging de-

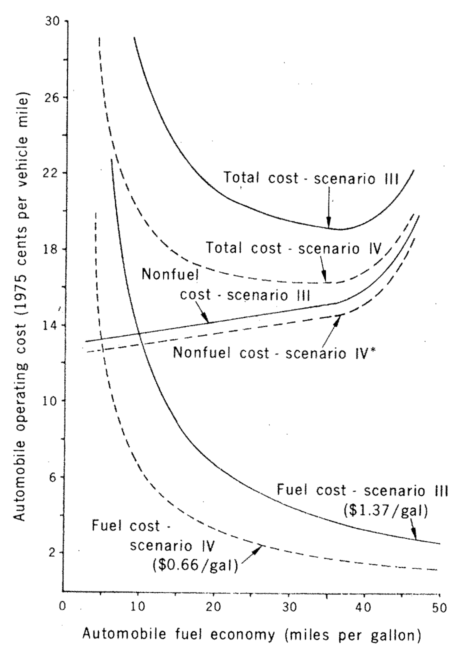

Fig. 8. Total cost of private automobiles plotted against mileage performance achievable by 1985. To provide approximately the same interior space, safety features, and so on, a more energy-efficient car is more expensive, but the added cost is not great for mileages less than 35 to 40 miles per gallon. Balanced against operating costs, the total cost of ownership and operation is remarkably insensitive to mileage. Note that nonfuel cost includes such items as depreciation, maintenance, garaging, parking and tolls, insurance, taxes and fees, and interest lost.

Table 6. Energy efficiencies in 2010, according to scenario II.

Buildings and appliances		Industry		Transportation	
Type	Intensity*	Type	Intensity†	Type	Intensity‡
Thermal integrity (heating)		Agriculture	0.85	Automobile	37 mpg
Residential	0.63	Aluminum	0.55	Light trucks and vans	30 mpg
Commercial	0.42	Cement	0.60	Air passenger	0.42
Government and education	0.35	Chemicals	0.74§	Truck freight	0.6
Space conditioning		Construction	0.58	Air freight	0.6
Air conditioning	0.66	Food	0.66	Rail freight	0.91
Electric heating	0.52	Glass	0.69		
Gas and oil heating	0.72	Iron and steel	0.72		
Refrigeration and freezing	0.58	Paper	0.64		
Lighting	0.60	Other industry	0.57		

*Energy intensity of new construction and products in 2010 compared with 1975. †Average energy per unit production in 2010 compared with 1975. ‡When figures are not given in designated units they refer to energy-intensity in 2010 compared with 1976 (including changes in load factor). §Excluding feedstock.

clines. Production of chemical foams and fiber glass for expanded thermal insulation increases; production of materials for strong but lightweight automobiles is expanded. Industrial cogeneration and power plant waste heat utilization become commonplace.

The most efficient automobiles, using new technologies such as the Brayton and Stirling engines, are introduced beginning in the late 1980's. Federal MPG standards set under the Energy Policy and Conservation Act of 1975 (Public Law 94-163) are reached and new standards are set, taking full advantage of the technological potential to increase mileage. People spend about 30 percent more time in cars, on the average, than in 1975. Air passenger miles per capita increase to a level about 60 percent greater than today's, while telecommunications technology improves substantially. Increased demand results in two generations of aircraft by 2010, which provide one-third more seat-miles per gallon. Airplane load factors increase from 55 to 75 percent as a result of government policy. Some modal switching from truck to rail occurs, and improvements in truck fuel efficiency and load factors yield substantial energy savings. Despite expanded per capita use (miles traveled, tons carried) the energy consumed in this sector in 2010 falls by 18 percent. Per capita use of mass transit expands nearly fivefold.

Scenario I. This scenario received less detailed attention than the others; it was derived by making incremental changes in the assumptions for scenario II concerning additional energy-conserving policy actions. As is the case for any level of energy use, many possible configurations of technology and life-style are compatible with an energy use of 59 quads at twice today's GNP. Here we describe only one set of changes relative to scenario II. We emphasize that such a scenario could not occur without aggressive, coordinated long-term policy actions in the areas of land use, transportation, and electric utility regulation. A more restricted set of policies limited to energy use (efficiency standards, energy taxes) probably could not achieve such a large reduction in energy use by 2010.

Energy use in buildings is reduced through improved building materials and construction techniques, including expanded use of passive solar design, and extensive use of such techniques as annual cycle energy systems, as well as active solar units. Continued migration to "sun belt" states occurs, along with acceleration of trends toward multifamily units. These measures combine to reduce end use for space conditioning and water heating to a level about one-third less than obtained in scenario II. Additional savings (about 1 quad) accrue from using steam from cogeneration in commercial and apartment buildings. An additional 0.3 quad of electricity is saved through further increases in the efficiency of appliances.

Substantial shifts occur in industrial production, favoring less energy-intensive goods. Major investments are made in new process technology and in new, highly efficient plants with cascaded use of heat. Since maximum practicable cogeneration (of electricity and industrial heat) was assumed in scenario II, no major additional improvements are assumed here.

The average time spent in automobiles (currently about 53 minutes per person per day) is reduced by 2010 to the 1963 average (43 minutes), in part because of better organized living patterns. This results in a savings of 1 quad of gasoline. In scenario II no improvement in the efficiency of military fuel use was assumed. In scenario I we assumed a 50 percent increase in effectiveness through improved efficiency, saving 1 quad.

No changes are made in the air transport sector beyond those in effect for scenario II. Energy use for freight transportation is reduced by one-third (2.0 quads) by shifts toward a more service-oriented economy and by strong policies promoting shifts from truck to rail transport.

The mix of goods and services constituting the GNP in all other scenarios showed only income effects, such as saturation of food purchases and increases in purchases of durable goods. If present trends continue toward higher prices for all resources (including energy) relative to labor, it may be expected that goods will be made more durable and will be maintained longer. Under such conditions the consumer market basket would shift away from goods toward services (including repair and maintenance).

Scenario I calls for significant changes in energy-consuming technology, and almost all activities become quite energy-efficient. The net result of these changes, in terms of primary fuel use, is a primary energy demand of 59 quads per year, corresponding to 60 percent of today's per capita energy. Scenario I may signal an approach to the level where energy and GNP become tightly coupled even in the longer term because presently anticipated technological improvements are fully utilized in scenario I.

Discussion of Results

Demand for electricity. The demand for energy as electricity has grown substantially faster than the demand for total energy (7.1 percent per year in the decade 1960 to 1970, compared to 4.2 percent per year for all energy). Analyses based on a broad range of assumptions suggest that the demand for electricity will grow substantially more slowly in the future. Ranges of average electricity demand growth are given in Table 7. These ranges are rather broad because of the ease with which electricity can be interchanged with other energy forms in new construction. Thus, an electric heat pump and a gas heating system are almost directly interchangeable. Similarly, for many industrial heat applications and ground-based transportation either electricity or gaseous or liquid fuels can be used. Only in a few applications does electricity appear to serve uniquely (lighting, specialized industrial applications, computers).

For the maximum electricity use analyses virtually all electric heating of buildings was assumed. In the industrial sector, the maximum (purchased) electricity scenario describes a situation where there is almost no self-generation of electricity, and where many processes are electrified. At the same time, the transportation sector was still assumed to operate primarily on liquid fuels. Major advances in electric energy storage (such as high-efficiency batteries) could change this situation significantly, however, and lead to even greater demands for electric energy than those included in the analyses given here. In the minimum electricity analyses, gas and oil provide virtually all heating needs, and electricity use is restricted to electric drive and other critical processes. Since the figures pertain only to electricity purchased from utilities, they understate the actual extent to which the industrial sector relies on internally generated electricity.

Economic effects. The scenarios imply a large potential for long-term change in the ratio of energy use to GNP. As long as the transition to energy-efficient capital stocks occurs smoothly and over a significantly long period of time, there is no reason to expect major adverse effects on the GNP. There appear to be no major differences in labor requirements between scenarios I and IV. Since only 16 percent of the labor force is employed in the sectors responsible for 70 percent of industrial energy consumption, the potential for appreciable impacts in that area is small. Labor in construction and maintenance of buildings, appliances, and automobiles could increase, offsetting reduced employment in energy- producing sectors.

Essentially all capital goods require energy (power plants, industrial equipment, buildings). Today about 25 percent of new capital available in the private sector goes for energy supply and conversion facilities (*16*). This is expected to increase in the future as more capital-intensive energy supply technologies are introduced (solar electric systems, synthetic fuel, nuclear plants). We assume for the purpose of analysis that this would increase to 30 percent in 2010 for scenario IV (energy prices about the same as today's). We will now consider the differences between this "nominal" case and scenario II.

In scenario II energy consumption is about 40 percent lower than in scenario IV, so we assume that the capital needed for energy supply facilities is likewise reduced by 40 percent to only 18 percent of total capital. This leaves 82 percent of new private capital available for energy-consuming stocks, representing about a 12 percent increase over the nominal 70 percent level. Each of the sectoral analyses indicated that the incremental capital cost of achieving scenario II efficiency levels is less than 10 percent of total nonenergy capital investment. Therefore, the capital not used for energy production could match or exceed the additional capital needed to improve energy efficiency of energy-consuming equipment.

Table 7. Role of purchased (utility) electricity (2010) in terms of total primary energy demand.

Sector	Scenario II*		Scenario III		Scenario IV		1975 (actual)
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	
Buildings, quads	10	22	13	25	17	43	12
Industry, quads	8	17	9	20	11	23	8
Transportation, quads†	1	4		4		4	
Total, quads	18	43	22	49	28	70	20
Primary energy, quads	74		94		136		71
Electricity, percent of primary energy‡	25	56	24	49	23	52	28
Average annual electricity growth, percent§	0.2	2.6	0.7	3.2	2.2	4.0	

*Electricity demand growth for scenario I was not estimated here. †A major shift to electricity for ground transportation is not assumed here. However, if about half of transportation were shifted to electricity by 2010 the additional electrical demand, beginning in 1990, would be ~5 GW/year. ‡These numbers represent upper and lower bounds, based on corresponding policies. The likely consumption in each scenario, barring such policies, is given in Table 2. §Over the period 1975 to 2010.

To check sensitivity to assumptions about GNP growth, the Panel considered another scenario in which conditions were assumed identical to those in scenario III except that the GNP is 40 percent higher in 2010 (nearly tripling instead of doubling the 1975 levels). Energy use increases by only 35 percent. This might be interpreted as implying an income elasticity of about 0.90, which is not inconsistent with the results of Herendeen and Tanaka (*17*) for the U.S. economic system in the early 1960's. This less than proportional increase in energy use is due entirely to shifts in the market basket of goods and services.

Conclusions

The purpose of this article has been to report on plausible energy futures corresponding to the low range of possible energy supplies. The Panel concluded that whatever driving forces might be involved, it will be technically feasible in 2010 to use roughly a total amount of energy as low as that used today and still provide a higher level of amenities, even with total population increasing 35 percent. It should be noted, however, that even under such low-energy scenarios there would still be enormous requirements for developing new energy supplies to replace depleted resources. The results of the analysis can be discussed in terms of responses to some frequently raised questions about the U.S. energy system.

Is a lower-energy future a bleak one for the United States? Probably the most important single finding of the study is that our national well-being can improve while energy growth is constrained to varying degrees. For this to occur requires higher energy prices, more regulation, or both. However, in every sector of the economy major increases in energy efficiency can be made by using presently available technology, and even greater improvements can be made with technology now under development. The large discrepancies between present energy efficiencies and those that are thermodynamically obtainable, together with economic analysis, show that improvements in efficiency of 1 percent per year or more are sustainable over a number of decades in the United States. If slower population growth trends continue, present amenity levels could be maintained and might be slowly expanded (at about half of past economic growth rates) without major increases in energy use.

Is a low-energy future a low-technology future? Probably just the reverse is true. A low-energy future offers strong incentives for technological innovation. In many recent inventions information has been substituted for energy. Modern computers and communication equipment perform better than past units but use only a small fraction of the energy. The techniques used to bring about energy reductions reported in this study in almost every case rely on the use of advanced technology.

If energy demand growth was so rapid in the past, how can it be so slow in the future without major effects? The most significant reasons for rapid energy growth since World War II have been the following.

- Steadily declining energy prices relative to the prices of other goods and services.
- Expanding consumer population.

• Introduction and rapid market penetration of energy-intensive consumer products that provide basic amenities (such as individualized transportation, comfortable habitat, and household conveniences).

• Increasing cost of labor, which increased the substitution of capital and energy for labor.

• Major increases in disposable income, enabling rapid expansion of consumer buying power.

None of these factors is likely to continue at its historic pace. Many past projections of energy futures simply did not take into account inevitable changes in these trends. Where they are taken into account, future demand growth is projected to be slower even without active conservation policies. In all the scenarios discussed in this article we assumed virtually complete saturation of the use of air conditioning and other major appliances by 2010, but did not explicitly account for new "phantom" appliances as energy-intensive as air conditioning. But neither did we count such new technologies as increasing energy efficiency. Considering that real energy prices will probably increase in the future, the latter type of technological development is more likely than the former.

The long-term substitutability of labor and capital for energy indicates that goods and services can continue to be provided in the future with less energy input. However, to do this requires other human and material resources. Therefore, unemployment in power plant construction is compensated by greater employment in constructing more energy-efficient commercial buildings and residences; lower requirements for steel in automobile construction are offset by an increased demand for aluminum and fiber glass; and control system designing for nuclear power plants is replaced by control system designing for space conditioning in commercial buildings. As long as these changes occur slowly, their impacts are minimized. It is essential to have time for adjustment.

What constrains our progress toward more efficient energy utilization? We have pointed out that existing products and technological know-how, if fully utilized, will permit major improvements in energy efficiency with little change in life-style. We can also be confident that improved technologies can be developed through R & D investments in this relatively unexplored field. Because there are already many technical opportunities for improved energy efficiency, we must conclude that the most important near-term constraints or impediments are not technological ones. They may be categorized as follows.

1) Price signals: energy consumers tend to weigh their conservation investment decisions against current average energy prices, whereas energy producers (such as utilities) weigh investment decisions against long-run incremental prices. Since energy prices at the margin are now usually considerably higher than average prices, producer and consumer investment decisions are not made on equivalent bases. Thus investments are biased toward increasing supply rather than moderating demand. This situation would be largely eliminated if prices were adjusted (as through an energy surcharge tax) to approximate long-run incremental costs.

2) Time: given time, changes that would be highly traumatic if made quickly can be relatively easy. Unfortunately, Americans have a tendency to want to do things instantly. (As Adlai Stevenson said, "We Americans seem never to see the handwriting on the wall . . . until our back is up against it.") Retrofitting is important and economical, but since the greatest technical opportunities to save energy can be achieved in new capital stock, it is clear that attendant efficiencies can be achieved only as that stock is replaced. The time needed for such stock turnover ranges from about a decade (air conditioners, automobiles) to a half-century (industrial processes). Time is also required to introduce new ways of designing and building energy-consuming items.

3) Standards and regulations: public policies that were developed when energy was cheap and plentiful frequently have the effect of constraining energy-conserving actions. These policies include natural gas price controls, freight transportation regulations, building codes, procurement procedures, and tax policy. Most of these are federal policies but there are also many state and local ones. Progress in energy efficiency that is rapid enough to meet national needs will require policies that directly influence energy-consuming activities.

If relative energy prices stay at about their present level, what is the likely future of demand? If we utilize available technology and make wise economic decisions (minimum total cost), future energy demand growth will be considerably slower than most past projections have indicated. Even a small increase in real energy prices provides a significant opportunity for cost saving through higher efficiency of energy use. Depending on the details of future events, U.S. energy consumption could actually peak within the next 20 years even though well-being continues to improve. But it seems more likely that demand growth will simply slow down. Much depends on public policies (especially those that affect investment), population growth, labor cost, consumer choices, and economic growth. Of this, however, we are certain: many of the principal factors that drove the high energy demand growth in the past are no longer with us.

References and Notes

1. The members of the CONAES Demand and Conservation Panel are listed in the author note. Its chairman is J. Gibbons. The Panel's Resource Groups and their chairmen are: Buildings, R. Carlsmith; Industry, M. Whiting; Transportation, E. Goodson; Integration, E. Bullard; and Economics, D. Chapman. Extensive technical assistance was provided by R. Barnes, E. Berndt, L. Colquitt, K. Friedman, E. Hirst, K. Johnson, T. Mount, D. Pilati, and T. Tyrrell. In addition in each Resource Group a number of experts from universities, business, and government contributed to the study. Although the Panel reached a consensus about the main points brought out in this study, there were individual differences of opinion about some details. These were small enough that no dissenting or minority opinions were recorded.
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19. The CONAES study has been conducted under the auspices of the National Research Council and supported in part by the Department of Energy.