UNITED STATES ENERGY USE FROM 1973 TO 1987: THE IMPACTS OF IMPROVED EFFICIENCY

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Annu. Rev. Energy. 1990. 15:455–504

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KEY WORDS: US energy efficiency, energy use and structural change, US energy demand since 1973, energy intensity, energy use trends.

INTRODUCTION

The purpose of this review is to investigate the evolution of energy demand in the United States since the early 1970s with the goal of measuring the impacts of improved energy efficiency. We examine the changes in final energy demand that were induced by changes in energy intensities, which are related to efficiency improvements; by changes in the aggregate activity levels in each major end-use sector; and by changes in the structure of activity within each sector. Where possible, we examine the changes in energy-efficiency trends caused by the drop in world oil prices in early 1986. Finally, we offer a view on prospects for enhanced energy efficiency over the long-term future.

Methodology

Studies of comparative energy efficiency often make use of aggregate indicators such as the ratio of primary energy use to Gross National Product

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(GNP). But the use of energy/GNP ratios as efficiency indicators is suspect on both theoretical and empirical grounds. The energy/GNP ratio is determined not only by changes in the efficiency of energy utilization, but also by changes in the growth of energy-using activities relative to GNP. As a recent study of the Norwegian economy shows (1) the effects of structural change on energy-output ratios may be substantial.

In this study we follow a fundamentally different approach. We examine the evolution of energy use in each major end-use sector and relate the changes that occurred to the effects of three causal factors: (*a*) changes in the aggregate level of energy-using activities in each sector; (*b*) changes in the structure or composition of activities; and (*c*) changes in energy intensities, or energy use per unit of activity or output. Of these three factors, only energy intensity (actually its inverse) is conceptually related to energy efficiency. Our work builds on and extends similar analyses performed by the Pacific Northwest Laboratory (PNL) (2) and the US Department of Energy (DOE) (3).

Our approach is one of factorization. For each sector we measure changes in activity, structure, and intensity and calculate the change in energy use that would have occurred in response to each factor if the other two had remained constant at base-year (1973) values. We then compare the overall activity change in each sector with the change in GNP. Where fuel switching is important we estimate the energy use that would have occurred in 1987 if fuel choice shares of 1973 had remained constant. Where possible, we disaggregate energy use by fuel type to circumvent the difficulties involved in the selection of an aggregate energy index (4).

We then seek to measure the impact of improved energy efficiency on total energy use by comparing energy intensities in 1973 and 1987, noting the differences, separating out the effects of fuel substitution where possible, and then multiplying each difference by the corresponding level of affected activity in 1987. For example, automobiles and light trucks in the United States required approximately 6.35 MJ/vehicle-km in 1973, but only 4.3 MJ/vehicle-km in 1987. Since these vehicles were driven 2.7 trillion vehicle-km in 1987, efficiency improvements "saved" 5.5 EJ of fuel, or about two and one-half million barrels per day of oil equivalent. These "savings" show how much more energy would have been used had intensity not fallen. While energy intensities are not strict indicators of energy efficiency because they are determined in part by behavioral and structural factors—the energy intensity of steel manufacture may, for example, decline either because of improved process technologies or because of increases in the utilization of scrap metal—energy intensities are observable while technical efficiency generally is not.

We summarize our findings by noting how major activities grew or contracted within each sector, and whether measures of overall sectoral activity grew more or less rapidly than GNP. Similarly, we can index the changes in intensity we observe to see which were rapid and which were slow, with an eye to the changes in the energy/GNP ratio. From this analysis we can identify the most important causes of change in US energy use since 1973, and hence likely sources of change—upward or downward—in the future.

In this approach we do not attempt to assign behavioral causes to energy savings. Thus while we refer to changes in prices and incomes that doubtless had fundamental impacts on the evolution of structure, energy intensity, and fuel choice, we leave a formal treatment of the impact of these factors for another study. But we do identify the physical components of energy saving, such as greater load factors in air travel, or a shift to slightly smaller automobiles. And where possible we attempt to distinguish between change that is reversible and change that is essentially permanent.

Sectors, Time Frame, and Data Considered

We focus on five energy use sectors—passenger transport, freight transport, households, the service sector, and manufacturing—that together account for approximately 80% of end-use energy as measured by the Department of Energy (Figure 1) (5). Our time frame is 1973 to 1987, although we have studied manufacturing energy use back to 1958, residential energy use as far back as 1960, and transportation energy demand back to 1970. The approach requires a reasonably accurate disaggregation of the residential and service sectors. We disaggregate manufacturing energy use from that of other industry, including the mining, agriculture, and construction sectors, about which little is known in spite of the fact that they used some 5.3 EJ of energy in 1985. Unfortunately, the last year for which the manufacturing sector data are disaggregated is 1985. We use a bottom-up disaggregation of energy use and activity for passenger travel, omitting travel by school bus. But we do estimate the important impact of light trucks on total passenger travel. For freight, we have estimated the haulage by light trucks but ignored natural gas use in pipelines (about 0.7 EJ in 1987) because there is no measure of natural gas movements. In all we estimate that the many uncertainties in energy demand and activity levels are smaller than the most important changes that have occurred since 1973. Hence we believe our conclusions are robust.

Summary Findings

Our principal findings are (see Table 1):

1. Aggregate energy intensities in the residential, services, manufacturing, freight, and passenger transportation sectors, adjusted for changes in the level and structure of sectoral activity, fell by a weighted average of 24% between 1973 and 1987. Adjusted primary energy intensities fell by a weighted average of 21%. Since the US energy/GNP ratio fell by 31.8% for delivered

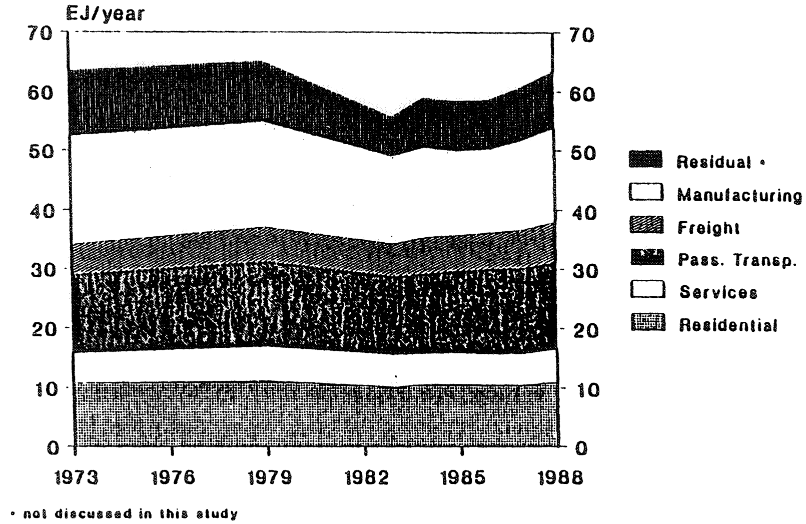


Figure 1 Delivered energy use by end-use sector. The residual category accounts for t difference between total delivered energy and the end-uses covered in this analysis.

energy and 26.3% for primary energy over this period, this analysis sugges that about three-quarters of the decline in the energy/GNP ratio was induc by reduced energy intensity, while the remainder was caused by structur change and interfuel substitution.

2. Actual energy use for the five sectors surveyed in detail was 51.4 EJ 1987, or 70.7 EJ including electricity generation and transmission losse Taking into account changes in the level and structure of energy-usi activities, the efficiency improvements described above translate into savin of 16.5 EJ of delivered energy or 19.7 EJ of primary energy.

3. The largest reductions in energy intensities occurred for automobile a air travel, home heating, and fuel use in the manufacturing and servi sectors. The energy intensity of truck freight, in contrast, actually increase A decline in load factors and a rise in the importance of light trucks f personal transportation together limited the decline in the system intensity private vehicles to only 15%.

4. The decline in fuel intensity for most fuel-using processes, together wi the increase in the number of electricity-using processes, caused the share delivered energy as electricity to increase from 11.2% to more than 16 Direct substitution of electricity for fuel in space and water heating or cooki had only a minor effect on this overall shift.

5. Changes in aggregate sectoral activity levels boosted delivered a primary energy use by 35%. But the activity levels of the freight, passen

Table 1 Impacts of changing activity levels, sectoral structure, and structure-adjusted energy intensity on sectoral energy use, 1973–1987

Indicator/sector	Definition/description of factors	Impact on sectoral energy use between 1973 and 1987: Delivered energy	Primary energy
Activity			
Passenger transportation	passenger-km/yr	+37%	+37%
Freight	tonne-km/yr	+28%	+28%
Manufacturing	manufacturing value-added	+43%	+43%
Residential	population	+15%	+15%
Services	service sector value-added	+50%	+50%
Weighted average[a,b]		+35%	+35%
Structure			
Passenger transportation	modal mix	+5%	+5%
Freight	modal mix	+4%	+4%
Manufacturing	industry-by-industry value-added shares	−17%	−16%
Residential	household floor area and appliance ownership per capita	+26%	+34%
Services	commercial floor area per unit of value-added, heating fuel switching	−1%	+6%
Weighted average[a]		+1%	+5%
Energy intensity			
Passenger transportation	modal energy intensities[c]	−20%	−20%
Freight	modal energy intensities[c]	−5%	−5%
Manufacturing	industry-by-industry energy intensities	−31%	−26%
Residential	useful space heat energy per unit of home area, electricity per appliance, useful energy per capita for cooking and hot water	−24%	−21%
Services	energy use per unit of commercial floor area	−29%	−18%
Weighted average[a,d]		−24%	−21%
Actual energy use			
Passenger transportation		+13%	+13%
Freight		+27%	+27%
Manufacturing		−21%	−13%
Residential		−3%	+13%
Services		+5%	+25%
Weighted average[a]		−2%	+6%

[a] Weights are shares of 1973 energy use
[b] Real GNP increased by 40% over the period
[c] Includes the impact of changes in load factors
[d] The energy/GNP ratio fell by 32% in terms of delivered energy and 26% in terms of primary energy

transportation, and residential sectors lagged behind the 40% growth in GNP while the proportion of GNP generated in the manufacturing sector remained relatively constant. Only service sector output grew more rapidly than GNP.

6. Structural change reduced manufacturing energy use but increased energy use in the residential, freight, and passenger transportation sectors because the mix of activities became more energy intensive. Overall, structural change within sectors increased US energy delivered use by only 1% and increased primary energy use by 5%.

7. The recent slowdown in the improvement of US energy efficiency has manifested itself in almost every sector, with the possible exception of manufacturing. This slowdown represents a market plateau, not the confrontation with thermodynamic or technological limits. Public policies could restore some of the interest in raising the efficiency of energy use.

TRANSPORTATION SECTOR

Total transportation energy use consists of four components: energy use for passenger transport, freight, natural gas pipelines, and a miscellaneous category that includes off-road equipment, private boats, military activities, and a number of other residual items (6, 7).[2] This section focuses on the first two components, which rose from 17.5 EJ in 1973 to 20.3 EJ in 1987[3] with temporary decreases observed following the oil shocks in 1973 and 1979 caused by declines in transportation activity.

Using data from Oak Ridge National Laboratory (ORNL), we describe the structure of each subsector by noting the contribution of each mode, measured by passenger-km or freight tonne-km, to total subsectoral activity. We obtain fuel use data from the same source. We measure vehicle fuel utilization intensity (VI) in MJ/km for cars and trucks and in MJ/air-km for aircraft. Complementing these fuel utilization indicators are *modal energy intensities* (MI), measured in MJ/passenger-km and MJ/tonne-km for passengers and freight, respectively. Estimates of both VI and MI are available; we use VI to describe technological changes that reduce the fuel use of individual modes and MI to compare modes. Note that the changes in VI and MI are often quite

[2] Our data follow Ross and the Oak Ridge Data Book, with one important added assumption: We estimate that light trucks provided 7% of passenger travel in private vehicles in 1970, rising to 22% in 1987. We assume that light trucks used as passenger vehicles are driven the same distance but with 10% higher load factors as automobiles. Data from the two Nationwide Personal Transportation Surveys that covered light trucks (1977, 1983) bear out this approximation. Our estimate of light truck fuel economy, however, is taken from values for all light trucks. Note that Ross uses vehicle-km as a measure of activity for autos/light trucks (and for truck freight), and gets somewhat different results because the volume of vehicle-km grew more than that of passenger or tonne-km in these modes.

[3] These figures represent 89% and 90% of sectoral energy use in the respective years.

different because of changes in utilization. These differences can lead to differences in the measurement of energy saved by as much as 25%.

The Structure of Transportation

The total volume of passenger travel increased by 2.2% per year between 1973 and 1987, slightly more rapidly than population, but slower than GNP. During this time the share of air transport increased from 6.5% to nearly 13% of total travel, at the expense of automobiles and light trucks (Figure 2). The share of bus and rail activity, which is low by international standards, fell from 2.4% of travel in 1973 to only 1.9% in 1987. Thus the shift from automobile to air was the major structural change occurring in this sector. If only the mix of modes had changed between 1973 and 1987, travel-related energy use would have increased by 5.3%.

The small share of rail and bus mass transit deserves comment. In some metropolitan areas mass transit carries as much as one-half of all trips to work, but private vehicles dominate all other travel. The long-term decline of the share of transit was reversed momentarily after the oil supply interruptions of 1973 and 1979, but has continued unabated since 1982. The fact that mass transit did not gain market share for any length of time while gasoline prices were high suggests that high energy costs alone were not sufficient to revive mass transit.

Related to the decline in the use of mass transit has been the increase in

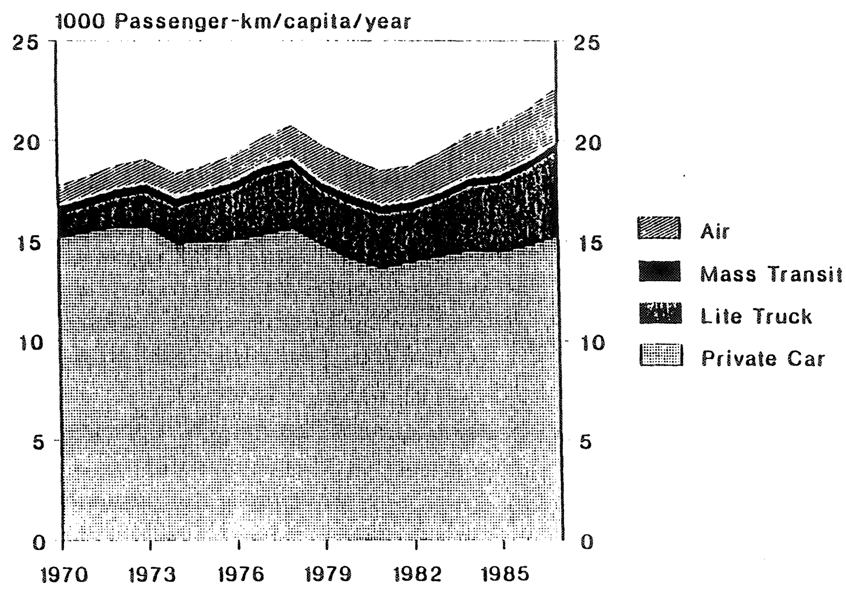


Figure 2 Passenger transporation per capita by mode.

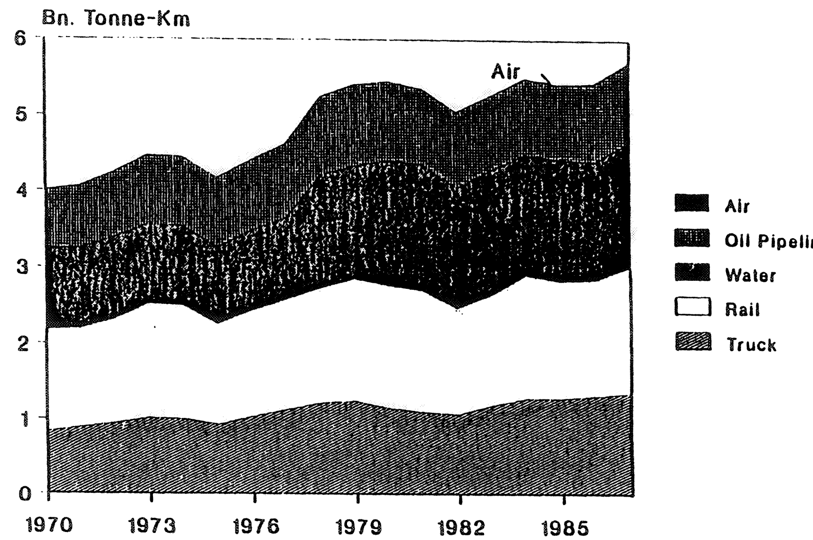


Figure 3 Freight activity by mode.

ownership of personal vehicles. The total number of automobiles and ligh trucks operated for personal use rose from less than 90 million in 1973 (0.4 per capita) to around 120 million in 1987 (0.60 per capita), or more than on vehicle for every person with a driver's license. But while the number of car and personal light trucks has grown steadily, the distance travelled per car pe year has been remarkably stable, even as fuel prices varied by more than factor of two (6). This increased vehicle ownership, and therefore greate driving per capita, not increased driving per vehicle, pushed total land trav upwards over time. All the increased ground travel has been carried by thes vehicles, resulting in a loss of share for bus and rail modes. Because loa factors in cars and light trucks declined from slightly more than 2 in 1973 t around 1.7 in 1987, the growth in passenger-km (1.8%/yr) in this mode di not keep pace with that of vehicle-km, 3.0%/yr.

The total volume of freight (excluding shipments of natural gas[4]) measure in tonne-km, grew at an annual rate of 1.8% from 1973 to 1987. Like travel freight grew less rapidly than GNP. The level of tonne-km by mode (excluc ing gas in pipelines) fluctuated over time (Figure 3). The share of truck increased slightly, and within trucking, the share of lighter, short haul truck

[4]Approximately 20% of freight energy use was in the form of natural gas used to r compressors for natural gas pipelines. Unfortunately, no measure of tonne-km for gas shipmen is available. Since natural gas substitutes for coal and oil, both of which are counted in freig shipments, the omission of natural gas is unfortunate. Similarly the small weight of water a coal-slurry shipped is also unavailable.

increased as well. If only the mix of modes had changes between 1973 and 1987, freight-related energy demand (excluding natural gas) would have increased by 3.6%.

Although the modal mixes for both passenger and freight transportation shifted towards modes with higher modal energy intensity, the volume of activity for each grew less rapidly than GNP. On balance, these changes reduced transportation energy use relative to GNP.

Intensity and Efficiency

Key energy-using vehicles became less energy-intensive during the 1970s and 1980s. The VI of automobiles fell by 33% to 4.3 MJ/vehicle-km or 19.1 MPG between 1973 and 1987. Light truck VI, which is higher than that of automobiles, fell less, by 19% to 5.9 MJ/vehicle-km. But the share of light trucks used as passenger vehicles increased to over 20% of the private passenger vehicle stock. When figures for these two vehicle types are combined, the result is only a 28% decline in the VI of private vehicles. The VI for air travel decreased by 22.7% between 1973 and 1987, to 305 MJ/km (7). Additionally, energy use per seat-km fell by more than 40% because the number of seats per aircraft increased from 111 in 1970 to 161 in 1987. Technologically, then, VI fell significantly for major modes.

Utilization patterns had different impacts on these modes. Load factors for automobiles and light trucks fell from approximately 2.0 occupants per vehicle in 1973 to 1.7 in 1987 (8).[5] As a result, the MI of private vehicle travel increased through 1979, and only fell 15% overall between 1973 and 1987. Load factors for transit buses fell, increasing energy intensity, but load factors for AMTRAK increased, causing the energy intensity of intercity rail travel to fall. Load factors for air travel increased significantly, from 54% of available seats filled in 1973 to 62% in 1987. This change, combined with the introduction of more efficient aircraft, caused the MI of air travel to fall by almost 50% between 1973 and 1987. Overall, the MI of passenger travel declined by 18% from 3.27 MJ/pass-km in 1973 to 2.69 MJ/pass-km in 1987. The decline in individual intensities alone caused a 20% decline in this intensity.

The fuel economy of automobiles improved significantly. As a review by Ross (6) shows, most of this improvement came about through improvements in the economy and performance of new cars of a given interior volume; "downsizing" of the fleet had only a minor impact on fuel economy. Furthermore, Ross shows that engine power per engine size increased. In other words, the performance of new cars sold in the United States improved, but

[5]Automobile load factors are estimated by ORNL from the Nationwide Personal Transportation Surveys (1969, 1977, 1983). Light trucks were included in 1977 and 1983. We have assumed that load factors and driving distances are approximately the same for both vehicle types.

VI fell. US Environmental Protection Agency (EPA) tests indicate that the sales-weighted fuel economy of new automobiles increased to 28.5 miles per gallon (mpg) (8.3 liters per 100 km) in 1988. The combined new car/light truck average moved from 15.3 mpg in 1975 to 25.8 mpg (9.2 liters per 100 km) in 1988.

Two factors prevented these dramatic improvements from fully affecting actual on-road fuel economy. Ross gives the test mpg of light trucks as 21 in 1988, down slightly from 1987, while that of automobiles rose to more than 28. The increased importance of light trucks with lower fuel economy than that of automobiles has thus restrained the improvement in overall new personal vehicle fuel economy. Second, the actual EPA tests do not represent real fuel economy, something well known for many years. This is because driving in the city is not well simulated in the EPA tests. Moreover, the distortion may have increased over recent years (9). The share of driving in cities has increased (DOE calls this the "rural-urban shift"), and the congestion in cities, which depresses fuel economy, has worsened. Thus test mpg may diverge as much as 22% from real mpg today as compared to the 15% bias of the 1970s. This distortion applies to light trucks as well as cars.

The dramatic improvement in air fuel economy was documented by Gately (10). New aircraft require significantly less energy per seat-mile than do older ones, both because of improved engines and aerodynamic characteristics (i.e. technology) and because most newer aircraft of a given type have more seats (i.e. structure). For example, a Boeing 767 yields more than 60 seat-miles per gallon, while a 707 of the original, pre-1960 vintage, gives less than 40. The number of seats on many older aircraft has been increased. In some cases, the engines on existing planes were upgraded, often in response to noise reduction regulations. As a result of these changes, seat-miles per gallon increased for almost every type of aircraft, typically from 30 to 40 for narrow-bodied planes (707s, 727s, and 737s) and from 40 to almost 60 for the wide-bodied models (747s, DC10s, and L1011s).

Changes in operations practices had an impact on fuel economy, too. As noted above, the average load factor increased (7). Stage length, or the distance flown per flight, increased by 23% from 742 km in 1978 to 917 km in 1988 (11). This change increased fuel economy, because planes spend a greater part of their flight actually cruising as stage length increases. Average speed should then increase, for the same reason. Yet average speed, as estimated by the US Federal Aviation Administration (FAA), was about the same in 1978 as in 1988. That average speed did not increase suggests that congestion around airports slows aircraft, increasing fuel consumption per trip as planes circle or take other measures near cities. It appears therefore that these two operational factors offset each other.

The story for freight was different than that for passenger travel. Ship and rail freight intensities each declined by about 30%. But truck freight intensities increased slightly by 6%, from 2.96 MJ/tonne-km in 1973 to 3.14 MJ/tonne-km in 1987.[6] Altered utilization patterns appear to be the reason for the increase in intensity, as well as a gradual increase in the importance of light trucks with low loads. Overall, the change in intensity of all modes alone through 1987 would have decreased freight energy use by 4.5%, but structural changes towards greater truck freight offset this decrease by 3.6%.

According to statistics cited by ORNL (7), the VI of light trucks, measured in MJ/km, fell by 19% between 1973 and 1987. The VI of other single unit trucks fell by 5% between 1973 and 1982 but has since increased over time. And the VI of combination trailer/trucks fell by about 5% over the entire period. When the entire stock is weighted using the Truck Inventory and Use Surveys of 1977 and 1982 (12), VI drops approximately 10%. Because these changes are so small, changes in the utilization and mix of trucks affected freight MI more than changes in the fuel economy of individual classes of trucks. The small improvement in fuel economy was more than offset by the other changes in utilization patterns that increased the energy intensity of freight haulage. In spite of the uncertainties, this finding suggests research is needed to improve the overall energy performance of trucking.

Conclusions: Energy Efficiency in Transportation

Between 1973 and 1987, the components of transportation energy demand changed significantly, as Figures 4 and 5 show. Overall, transportation energy use declined relative to GNP. The most important single component in this decline was the reduction in the energy intensity of passenger travel. The vehicle efficiency of the three major transportation modes has improved since 1973. Fleets of personal vehicles, aircraft, and trucks were 28, 40, and 10% less energy intensive in 1987 than they were in 1973. This change alone saved more than 7 EJ/yr of energy by 1987. Lower load factors in personal vehicles increased energy use by 1.4 EJ, and lower load factors and shifts to more local freight traffic increased energy use for freight by more than 0.6 EJ. Although our figures are not strictly combinable in a linear way, the savings implied by these three changes are consistent with the 4 EJ that PNL and DOE estimated were saved between 1972 and 1986.

In 1989 the VI of new personal vehicles and aircraft was approximately

[6]Unfortunately there are no complete data for US freight haulage, only estimates of intercity tonne-km and energy use. Freight carried by light trucks was estimated by assuming they carry 100 kg for the vehicle miles not assigned to personal light trucks. Intracity freight carried by heavy trucks was estimated from the difference between vehicle-miles of heavy trucks in intercity travel and in all travel, multiplied by 2.5 mt to represent a load. Over a wide range of assumptions for these values there seems no question that the total energy used by trucks increased faster than the total volume of freight.

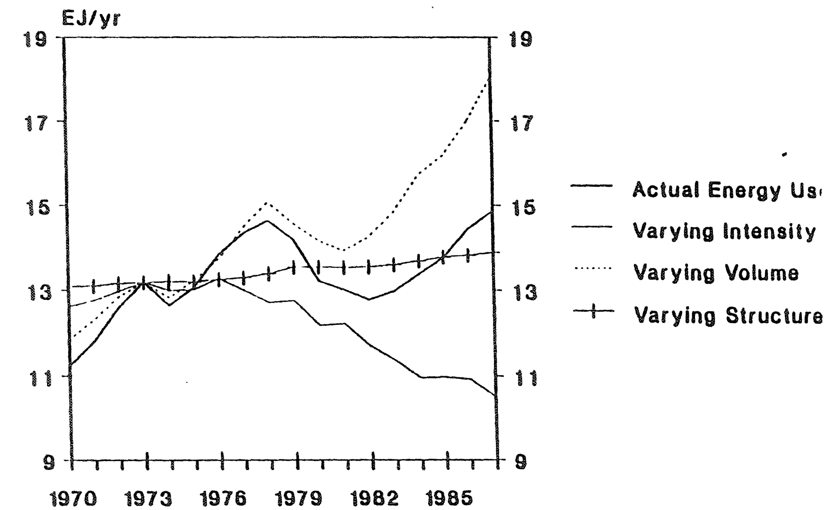


Figure 4 Passenger transportation delivered energy use. Evolution of actual and hypothetic transportation energy use for travel. Each "effect" is computed by having only modal intensit activity, or structure (modal mix) follow its actual path while holding the other two componen constant at 1973 levels.

25% less than that of the existing vehicle stock, ensuring technologic decreases in fuel needs that are irreversible for the next several years. Bu whereas the load factors of aircraft increased in the 1970s and early 1980 lowering MI even more, utilization of both automobiles and trucks worsene in the latter case enough to cause an increase in MI. And preliminary da suggest that the automobiles and light trucks purchased in 1989 will be mo fuel intensive than those purchased in 1988. The VI of other trucks stoppe declining in 1982. Moreover, preliminary operating data from 1988 sugge that fuel use per passenger-km for commercial aviation in 1988 was no low than in 1987. And average speed was headed downward, suggesting mo congestion at airports. Thus the rate of improvement in actual fuel economy major transportation modes is clearly slowing down. While all three mod show promise for further improvements in technological efficiency, the improvements have been slowed by lower fuel prices and other factors.

OUTLOOK

Automobile transport is the single most important energy-using activity in t US economy. Thus changes in the fuel economy of cars will be important

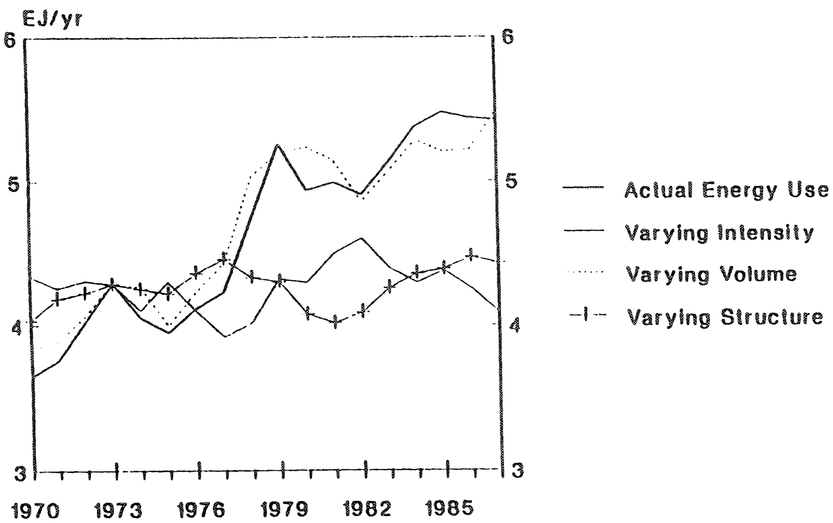


Figure 5 Freight transportation delivered energy use. Evolution of actual and hypothetical energy use for freight transportation. Each "effect" is computed by having only intensity, activity, or structure (modal mix) follow its actual path while holding the other two components constant at 1973 levels.

the nation's energy future. Not surprisingly, there is concern over the recent flattening of the fuel intensity of personal vehicles. Figure 6 shows key features of this plateau. Indexed to real (or estimated) 1973 values are actual fleet and test new vehicle fuel intensity (including that of light trucks) as calculated by Ross (6), the real gasoline price, the real cost/km of using gasoline, i.e. the price index times the fuel utilization index. The sudden decline in price (and cost) in 1986 is clear, as is the slow drop of equal magnitude between 1982 and 1986. Not surprisingly, the decline in fuel intensity slowed after 1982 and may have reversed in 1989. Indeed, the fuel economy of cars imported into the United States peaked in 1983. Have auto manufacturers exhausted ways of improving fuel economy?

The literature is replete with reviews of the potential for further improvements in fuel economy (6, 13–17). These references all point to a large number of prototype cars that use less than 50% as much fuel per seat-km as today's average new car, and hence less than 33% of the present fuel per km. In conversations with major automobile producers worldwide (including BMW, Volkswagen, Volvo, Peugeot, and General Motors), however, we found that the outlook for stable oil prices has all but erased fuel economy as a major concern for auto manufacturers. Similarly, the lull in gasoline prices has permitted, if not encouraged, Americans, Japanese, and Europeans to

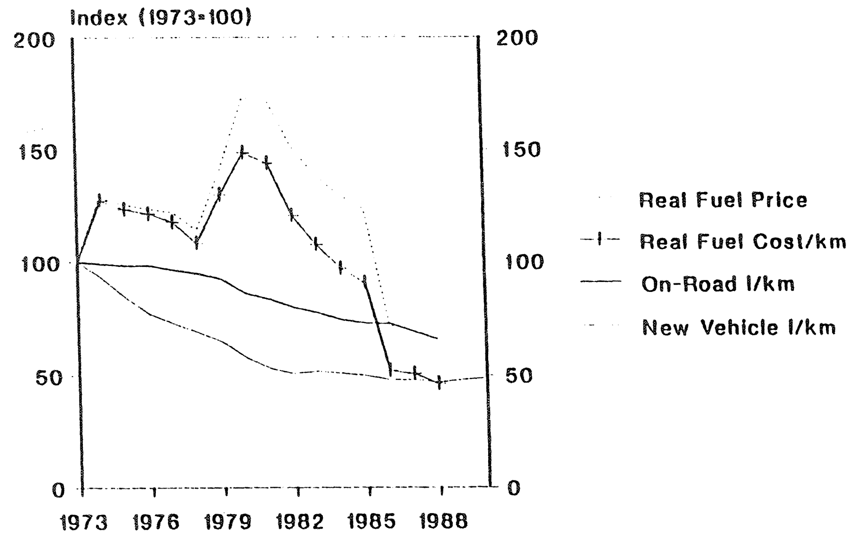


Figure 6 Personal vehicle fuel economy. Evolution of new-car and on-road fleet mpg and prices in the United States. Prices are taken from *Monthly Energy Review*. The on-road vehicle fuel economy figures are calculated in this study by summing values for cars and personal light trucks. The new vehicle figures include all light trucks sold. Sources: ORNL, ACEEE, LBL-IES

manufacture and buy more powerful and often larger cars in recent years. Thus the plateau (and apparent reversal) in the weighted improvement in fuel economy are as much a result of consumer indifference as of manufacturer disinterest. As Ross (6) shows, total driving costs are relatively insensitive to fuel costs. This was particularly true in 1988, when the real gasoline cost of driving one km in the United States and many European countries was the lowest in decades.

Difiglio et al (17) catalogue technologies that would improve test new-car fuel economy to nearly 40 mpg with no loss in amenity. Using a 7% real discount rate and amortizing the increased costs over 10 years, Carlsmith et al (18) found that improvements to 38.5 mpg would be cost effective at a gasoline price of $1.43/gallon in 2000. But these discount rates are not typical for consumers' purchases of energy-using goods, as Rudermann et al showed for appliances (19). Greene (20) finds that both the Corporate Average Fuel Economy (CAFE) standards and to some extent higher fuel prices caused the decline in fuel intensity after 1975, stimulating both consumers and producers to focus on fuel economy. But with standards frozen today, there is no pressure from this powerful stimulus. Moreover, with fuel prices and costs as low as they were in 1989, it would be difficult to believe that fuel intensity would continue to decline rapidly, although technological improvements could certainly keep pace with increases in interior room and power. The high-mpg prototypes may never be commercialized, although important components tested in these models may appear soon in ordinary automobiles. Standards of some kind, combined with higher fuel prices, possibly through taxes, appear necessary components of any policy designed to get both producers and buyers to focus on fuel economy in the near future.

The fuel economy of trucks should not be overlooked. Better engines, better aerodynamic designs, and, in some states, permission to pull two trailers, all could contribute to lower VI. But the truck freight system itself has evolved towards a more energy-intensive mix of short haul modes and smaller trucks, as a result of shifts in the kinds of products being shipped and the patterns of shipping. And traffic congestion increases truck fuel use. While the intensities of other freight modes have declined since 1973, these modes have played a declining role vis-a-vis trucks, whose fuel use dominates the subsector. As a result, the probability that the energy intensity of freight hauling will fall over the short term future is slim.

The third most important subsector of transportation is air travel. According to experts at Boeing (D. Wallace, private communication), three important factors will affect future passenger aircraft fuel economy. Gradual improvements in control technologies will reduce energy requirements somewhat; breakthroughs in materials technologies that permit engines to operate at higher temperatures could boost engine performance significantly; better scheduling and controlling will reduce losses at and around airports. Each of these changes could reduce fuel intensity by 5–10%. More dramatically, adoption of the by-pass fan engine would reduce fuel intensity by 30% or more. But both Boeing and McDonnell-Douglas have put off development of this engine indefinitely. The cost of new developments, expressed as an incremental capital cost for new aircraft, is too high relative to the cost of fuel. Hence expectations are for only gradual improvements through better flying controls.

Just as for automobiles, aircraft energy intensity also depends on system performance. Passengers per flight increased all through the 1970s and 1980s, but recently airlines have found it profitable to insert business class seats in place of economy, reducing the total seating/aircraft available. Congestion at and around airports is another factor affecting energy intensity. And stage length also has a fundamental impact on fuel use. Nevertheless, virtually every new airplane entering the US (and world) fleet is more efficient than the present fleet itself. This efficiency gain is greater than the potential offsetting effects of slight declines in seating capacity or load factor. Thus the principal uncertainty over future aircraft fuel performance is that of the rate of decline of fuel intensity.

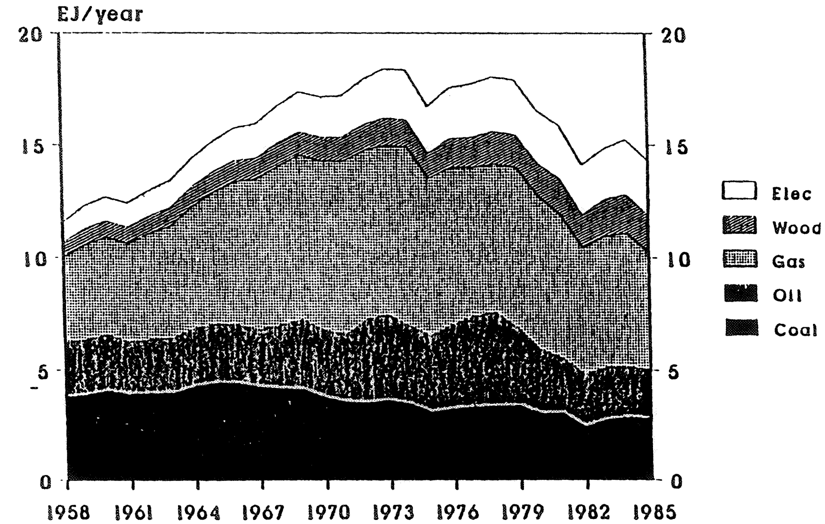


Figure 7 Manufacturing energy use by fuel type.

MANUFACTURING SECTOR

The US manufacturing sector, which consists of a range of industry group involved in the transformation of raw materials and intermediate goods int finished products, used 14.3 EJ of energy for the provision of heat and powe in 1985 (Figure 7). While an additional 4.1 EJ of energy products were use by the sector as feedstocks in the production of asphalt, organic chemicals and other goods, these products were excluded from our analysis on th grounds that they should properly be counted as material rather than energ inputs.

We gathered data on the energy use and economic activity of six energy intensive manufacturing industry groups—paper and pulp (SIC[7] 26); industrial chemicals (SIC 28 excluding 283–285); stone, clay, and glass (SIC 32); iron and steel (SICs 331, 332, and 339); nonferrous metals (SIC 333–336); petroleum refining (SIC 291)—and a residual category ("other" that encompasses the range of non-energy-intensive manufacturing activities

Unfortunately, the available statistics on manufacturing energy use are les than adequate in a number of respects. Although the Census Bureau (21, 22 published data on manufacturing energy use for the years 1954, 1958, 1962 1967, 1971, and 1974–1981, this series was discontinued in more recent year as the federal government cut back its efforts to gather and publish energ data. Moreover, the Census data account only for inputs of purchased fuel

[7] "SIC" is an acronym for the US Standard Industrial Classification system.

and electricity, and exclude self-produced fuels such as the still gas used in petroleum refining and the wood waste used in the paper and pulp sector that together account for some 29% of sectoral energy use. More recently, the Energy Information Administration (EIA) carried out a survey on manufacturing energy use (23) that both provided data for the 1985 calendar year and measured the use of nonpurchased fuels. But while EIA plans to repeat this survey at three-year intervals, no comprehensive data on manufacturing energy use are available past 1985.

The manufacturing energy data used in this report were taken from the US National Energy Accounts (NEA) (24), which use a variety of government and nongovernment statistics—including the Census and EIA data—to provide a consistent series of annual energy use data for the years 1958 to 1985. These data account for the total use of fuels and electricity for heat and power and distinguish between oil, natural gas, coal, wood, and electricity consumption.

The measurement of manufacturing activity involves both conceptual and practical difficulties. While the real value-added statistics published by the Commerce Department (25) are often used in the analysis of trends in industrial production, these data are estimated as the algebraic difference between dollar values of outputs and intermediate inputs in each year, evaluated at base-year prices. Consequently, trends in Commerce Department real value-added depend not only on output trends per se but also on changes in the efficiency with which inputs are used to produce output. Value-added will increase, for example, if production remains constant but technological improvement leads to reduced input requirements per unit of output.

To circumvent this difficulty, the Industrial Production Indices published by the Federal Reserve Board (FRB) (26, 27) were used to measure manufacturing activity for the purposes of this study. These statistics measure the physical production of each product class weighted by its contribution to sectoral value added in the base year (1977). The result is a series of real value-added data that in principle account strictly for changes in physical production.[8]

The energy intensity of each industry group is thus defined as energy use per unit of FRB industrial production, measured in energy per unit of value-added. Our analysis investigates the impacts of changes in the level of sectoral output, changes in the structure or composition of this output between industry groups, and changes in industry-by-industry energy intensity on the evolution of manufacturing energy use.

[8]Unfortunately, physical production is not readily defined in certain industry groups. As a result, the FRB makes limited use of data on inputs—including, in some cases, electricity consumption—as surrogates for output. While this practice obviously compromises the quality of the data to some extent, the application of this technique is limited to a small number of industry groups.

The Structure of the Manufacturing Sector

The manufacturing sector consists of a large number of diverse industry groups that employ an even broader range of process technologies to transform raw materials into finished goods and services. This inherent complexity imposes certain limitations on energy analyses that do not generally hold for other end-use sectors. In the residential and transport sectors, for example, it is possible to relate energy use to specific technologies and to measure efficiency changes explicitly over time. In the manufacturing sector, on the other hand, one must either carry out detailed technological analyses of particular processes or facilities or else focus on the analysis of relatively aggregated data.

The analysis is greatly simplified, however, by the fact that manufacturing energy use is largely dominated by sectors involved in the processing of raw materials. The energy-intensive industry groups described above, although they account for only 18% of manufacturing value-added (Figure 8), are responsible for 56% of sectoral electricity use and 74% of total energy use (Figure 9). Accordingly, shifts in the product mix between the various energy-intensive industries or between raw materials and light manufacturing may have significant impacts on sectoral energy use.

To gauge the impacts of structural change on manufacturing energy use we calculated the evolution in energy use broken down by fuel type that would have occurred if the total output level and the energy intensities of each

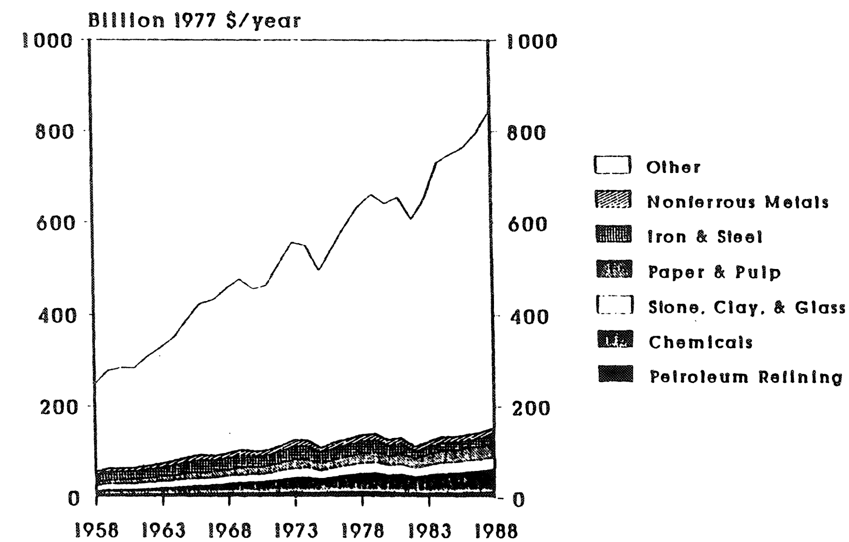


Figure 8 Manufacturing activity. Value-added by subsector.

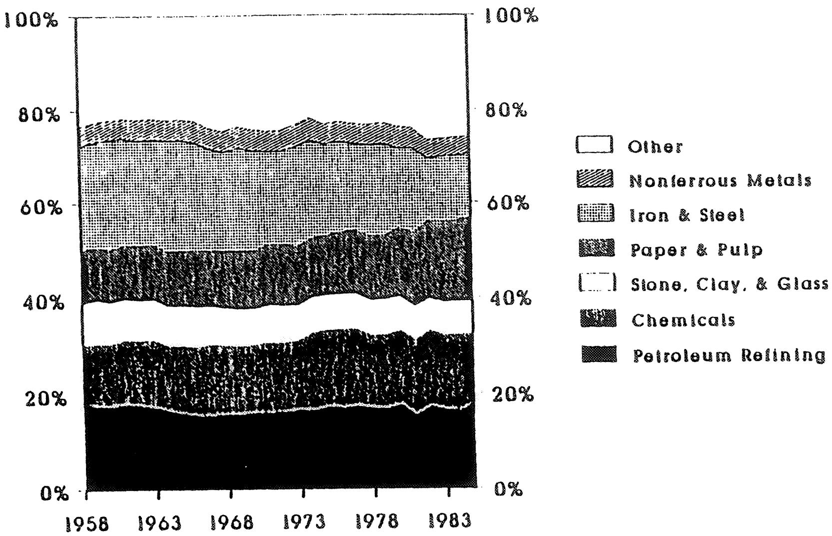


Figure 9 Manufacturing energy use. Shares by industry group.

industry group had remained constant at their 1973 values while the proportion of output produced by each industry followed its historical development. We found that structural change had no significant impacts on energy use between 1958 and 1973. Between 1973 and 1985, however, structural change at constant output and energy intensity would have depressed energy use by 18%, or 1.6% per year (Figure 10).

The impacts of structural change were driven largely by a decline in the proportion of output produced in coal-intensive industries—particularly the iron and steel sector, which alone accounts for one-third of manufacturing coal consumption. While structural change would have reduced coal use by 33% between 1973 and 1985, the corresponding reductions in oil, gas, and electricity use were 16%, 16%, and 10% respectively. These results suggest that rising oil prices were not the most important factor driving structural change. A number of analysts have suggested that a long-term reduction in the materials intensity of the US economy that has significant energy implications has been under way (28). Indeed, the physical production of certain raw materials such as steel fell significantly during the 1970s and 1980s, although the production of other commodities such as plastics increased (29). But other factors, such as macroeconomic policies that have given rise to high interest rates and a strong dollar that have placed the US raw materials sector at a comparative disadvantage, have also been important. Over the one-year period 1981–1982, for example, the output of the iron and

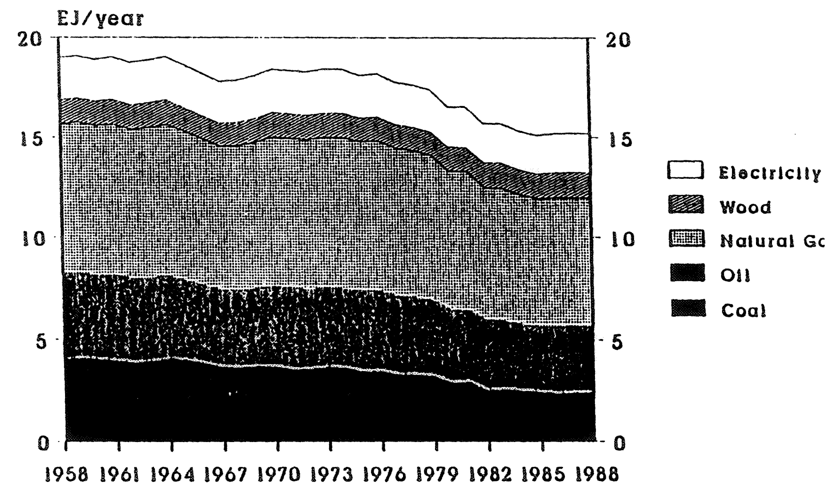


Figure 10 Manufacturing energy use. Impacts of structural change. This shows the hypothetic evolution of energy use in manufacturing if activity and intensities had remained constant at 197 levels and only the value-added shares of the subsectors (structure) had followed their actu paths.

steel sector fell by 37% during the strong recession. This change alone yielde an energy use reduction of 1.1 EJ, or 7% of manufacturing energy use.

Structural change had no measurable impacts on energy use between 198 and 1988, either in aggregate terms or on a fuel-by-fuel basis, at the level o aggregation employed in this analysis. In recent years, raw materials produc tion, as measured in economic terms, has kept pace with aggregate man ufacturing activity. These results suggest that the expectation that shifts in th composition of manufacturing value-added away from energy-intensive in dustries will lead to significant future energy savings may not be fulfilled, o at least that the anticipated decline may not be smooth and continuous.

The rate at which manufacturing output grows over time is also an impor tant determinant of sectoral energy use. Real manufacturing value-added gre at the rapid rate of 5.4% per year between 1958 and 1973 and at the slower bu still substantial rate of 2.7% per year between 1973 and 1988 (Figure 8). Thu sectoral growth placed strong upward pressure on energy use throughout th period of analysis. Changes in the growth rate of manufacturing productio relative to GNP are a structural effect of particular relevance to manufactu ing energy use. But while some analysts have argued that the economi importance of manufacturing has declined significantly over time, the dat point to a different conclusion. The fraction of real US GNP generate by the manufacturing sector remained more or less constant at 21% in th 1970s and 1980s with only minor changes induced by business cycl fluctuations. Manufacturing output, as it is conventionally measured, has grown with the economy for the past two decades, and there is no particular reason to believe that this relationship will decouple over the short to intermediate term.

Intensity and Efficiency

Changes in energy intensity, or energy per unit of value added in a particular industry, will reflect changing efficiency perfectly only if there is no change in the mix of products produced within that industry. Our preliminary analysis of the ratio of the physical production of energy-intensive raw materials to real value-added in the industry groups in which those materials are produced has shown that structural changes may have been important in sectors such as chemicals, where the production of plastics increased substantially relative to other commodities; and in stone, clay, and glass, where the production of cement fell by 20% relative to value added. But the literature to date has shown that the most important impacts of structural change may be captured at a relatively high level of aggregation such as the one used in this analysis (30, 31). Thus while the figures discussed in this section should be regarded properly as indicators rather than measures of energy efficiency, we believe that energy-intensity trends as measured in this analysis are driven mainly by efficiency improvements.

To measure the impacts of changing energy intensities on manufacturing energy use, we estimated the evolution in energy use that would have occurred between 1958 and 1985 if the output of each industry group had remained constant at its 1973 value while its energy intensity followed its historical path. According to this calculation, structure-adjusted manufacturing energy intensity declined by 2.5% per year between 1958 and 1973 (Figure 11). While this decline was led by a 58% decline in coal intensity, the intensity of oil, gas, and wood use declined by 23%, 15%, and 17% respectively. Electricity intensity, on the other hand, remained relatively constant over the period.

The 1973 to 1985 trend in energy intensity is remarkably similar. On aggregate, structure-adjusted energy intensity fell by 2.7% per year between 1973 and 1985—only slightly more rapidly than the 1958–1973 trend. On a fuel-by-fuel basis, the intensity reductions were 44%, 37%, and 15% for oil, gas, and coal, respectively. Wood intensity increased by 6%, while electricity intensity dropped by some 6%.

Together, these statistics point to considerable improvements in manufacturing energy efficiency over time. But these changes were arguably driven as much by long-term changes in process technologies as by short-term responses to changes in the relative price of energy. It is indeed striking and even counterintuitive that the energy shocks of the 1970s did not induce a significant increase in the rate with which manufacturing energy intensity

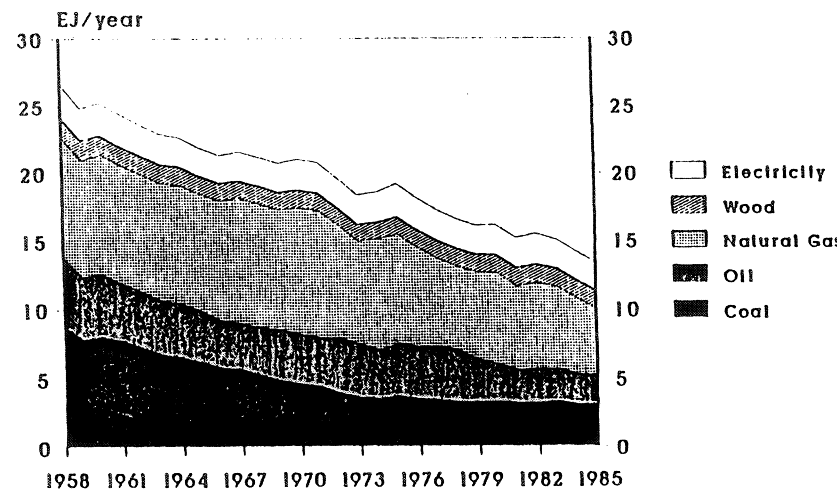


Figure 11 Manufacturing energy use. Impacts of intensity changes. This shows the hypothetical evolution of energy use in manufacturing if activity and value-added shares of the subsectors (structure) had remained constant at 1973 levels and only intensities had followed their actual paths.

fell. Should not higher energy prices have pushed producers to develop and implement energy-saving technologies that were not cost-effective at the low energy prices of the 1960s?

The following line of reasoning may explain this observed disparity between expectation and realization. Energy accounts for only a small fraction of total input costs in all but the most energy-intensive industries, so research and development programs generally focus more on capital and labor productivity and product quality than on energy saving. But technologies that produce capital and labor savings generally save energy as well, so that the energy efficiency of new manufacturing technologies improves over time, even at low energy prices. The energy price increases of the 1970s presumably led producers to invest in focused energy-saving technologies. But the annual rate of manufacturing output growth slowed from 5.4% between 1958 and 1973 to 2.5% between 1973 and 1985. Hence while new technologies may have been designed with more attention to energy costs, investments in new technology slowed along with output growth. On balance, then, the rate of energy-efficiency improvement remained more or less constant.

Manufacturing Energy Intensity, 1985–1987

As noted above, the most recent year for which comprehensive data on manufacturing energy use are available is 1985. It is therefore not feasible to extend the analysis presented in the preceding section to more recent years. Data are available, however, on the use of fuel and electricity for heat and power in the aggregate industrial sector, which includes manufacturing, mining, agriculture, and construction. These data were prepared by subtracting the use of energy feedstocks from the industrial energy statistics published by the Energy Information Administration (32). If we assume that the rate of energy-intensity change was the same in manufacturing and nonmanufacturing industries, and that structural shifts between manufacturing and other industries were small, then changes in the ratio of industrial energy use to total industrial production give an approximate measure of recent trends in manufacturing energy intensity. When this calculation is carried out, we find that aggregate energy intensity fell by 4.1% between 1985 and 1987; fuel intensity fell by 4.6%; and electricity fell by 1.9%. These savings were focused mainly on the 1985–1986 interval. Little change in energy intensity occurred between 1986 and 1987; electricity intensity actually increased by 1.2%. (See NOTE ADDED IN PROOF on p. 501.)

While this approach lacks analytical rigor, it is defensible on the basis that the manufacturing sector accounts for some two-thirds of industrial production and four-fifths of industrial energy use. As we noted above, structural change had no significant impacts on manufacturing energy use between 1985 and 1987. Moreover, the composition of total industrial production between the various component sectors did not change substantially over the period. In any event, such casual analysis will have to suffice in the absence of more authoritative data.

We note, however, that recent trends in selected industry groups support the hypothesis that energy intensities are continuing to fall even in the post-1985 era of low energy prices. Unpublished data from the Iron and Steel Association (E. Young, private communication), for example, indicate that the energy intensity of that sector fell by 11.5% between 1985 and 1988, or 4.1% per year. This improvement was spread across the range of technologies used in the industry. Similarly, statistics from the American Paper Institute (J. Metz, private communication) indicate that an energy intensity reduction of 2.1% occurred in the paper industry between 1987 and 1988. This number grows to 7.5% when adjustments are made to account for changes in capacity utilization, the fuel mix, and other "structural" factors. Since the annual reductions averaged 3.2% between 1972 and 1988—or 3.5% on an adjusted basis—it is clear that recent improvements are consistent with long-term trends. Energy intensity also fell in the chemicals sector between 1985 and 1988 according to unpublished data from the Chemicals Manufacturing Association (T. Parker, private communication). While the use of fuels and electricity consumed for heat and power increased by 14% over the period, sectoral output increased by 20%. Thus energy intensity fell by a total of 5.0%, or 1.7% per year.

Fuel Mix

The use of oil and natural gas fell rapidly as the prices of these fuels rose i the 1970s. It is often suggested that one of the factors behind this trend wa the substitution of solids and electricity for oil and gas. Indeed, the man ufacturing fuel share of wood rose from 7% to 12% between 1973 and 1985 while the electricity share rose from 12% to 17%. The coal share, in contrast remained constant. But the utilization intensities of these fuels did not ris substantially over the period—indeed, electricity intensity, adjusted t account for the impacts of structural change, decreased by 6%. Thus whil interfuel substitution was undoubtedly important in some applications, on th whole oil and gas savings were apparently generated more by conservatio than by substitution.

Conclusions: Energy Efficiency in Manufacturing

We have documented that enhanced energy efficiency has been an importar factor shaping the development of manufacturing energy use. But just ho much energy was saved by the energy intensity reductions that occurre between 1973 and 1987? The fact that statistics are not available on actu manufacturing energy use in 1987 complicates the analysis. But if we assum in light of the information presented above that aggregate manufacturing fu intensity fell by 4.6% between 1985 and 1987 while electricity intensity fe by 1.9%, and multiply these intensity estimates by actual 1987 manufacturin activity, we find that the manufacturing sector used approximately 12.1 EJ c fuel and 2.5 EJ of electricity in 1987. If, however, the energy intensities c each industry group had remained fixed at their 1973 values, manufacturin fuel and electricity use would have been 19.0 EJ and 2.8 EJ respectively give the actual level and structure of output in 1987. Thus energy intensi reductions between 1973 and 1987 saved about 6.9 EJ of fuel and 0.3 EJ c electricity for an overall improvement of 33%.

Outlook

Future energy use trends in the manufacturing sector, as in the other secto considered in this analysis, are difficult to divine. In the absence of compe ling evidence to the contrary, we expect that manufacturing output wi continue to grow more or less with GNP. A number of analysts have su gested that the structure of manufacturing production will continue to evol away from energy-intensive raw materials industries (28). But the structure manufacturing has apparently stabilized in recent years, halting the downwa pressure on energy use that persisted throughout the late 1970s and ear 1980s. Future structural trends are therefore highly uncertain and deser further research.

The future of manufacturing energy efficiency, on the other hand, is mo easily forecast. As we noted above, sectoral energy intensity declined at an average annual rate of 2.6% per year between 1958 and 1985 with no significant departures from the trend over the entire period. Moreover, a range of studies have suggested that a continuing improvement of 1–2% per year will be realized under expected economic conditions through the turn of the century (28, 33, 34).

Of particular interest is a series of engineering studies of the potential for efficiency improvements in five industries—steel, cement, paper and pulp, glass, and textile manufacturing (35–39). The studies indicate that the chances are "very good" that the aggregate energy use per unit of physical production of the sectors in question could be reduced by roughly 30% (1.4% per year) between 1985 and 2010 using current "state of the art" technology. Reductions of approximately 40% (2.8% per year) are "possible" based on the use of advanced technology.

The extent to which new energy-efficient technologies penetrate the manufacturing sector will be generated in part by the rate of output growth (which determines investment in new facilities) as well as by energy prices. But we expect that manufacturing energy intensity will continue to decline at a healthy rate, although perhaps not as rapidly as in the past, as cost-conscious managers seek to cut production costs.

RESIDENTIAL SECTOR

Total final US residential energy use remained relatively constant in the 1970s and 1980s, fluctuating between a high value of 10.9 EJ in 1979 and a low of 10.0 EJ in 1982 (Figure 12), but rising to nearly 11 EJ by 1988. Primary energy use, however, rose over most of the period with plateaus in the years following each energy shock (40).[9]

During this time period, important changes took place in the characteristics of the sector and the fuel mix. Population, which we take as our measure of residential activity, and the number of dwellings increased substantially, and the fuel mix changed as well. We must further disaggregate energy use by fuel and end use in order to separate the effects of these changes from the impact of greater efficiency. To do this, we compare energy use for appliances, hot

[9]These data are based on the State Energy Data System (SEDS) reports, but include wood as estimated by the Energy Information Administration and the use of gas and oil in apartment buildings, uses of energy omitted from SEDS. Weather adjustment is carried out by dividing the apparent consumption of electricity and fuels for space heating by the ratio of actual to long-term average degree-days. When individual fuels are compared over time, the degree-day series account for the distribution of homes heated by each fuel.

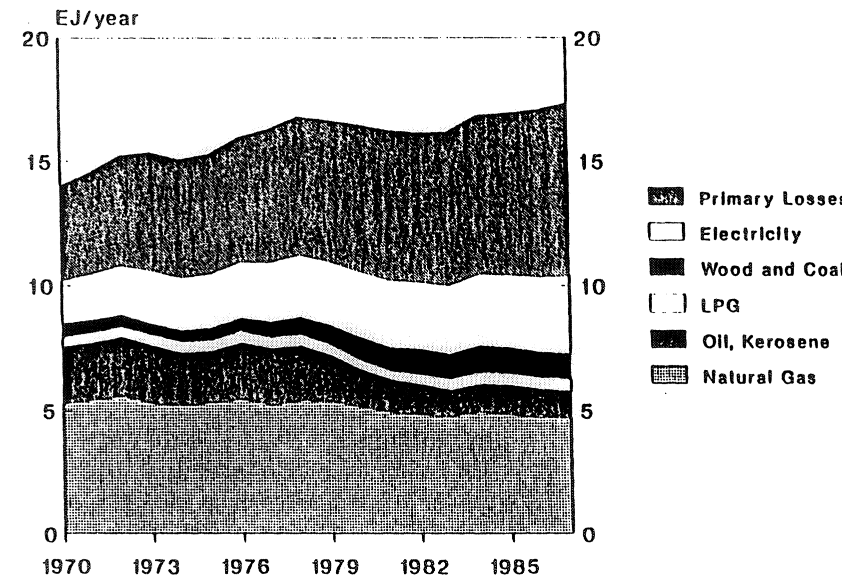


Figure 12 Residential energy use. Energy use by fuel.

water, and cooking (41) with household population, and we compare space heating with the number of homes or, where data are available, with square meters of heated floor area. These comparisons yield energy intensities that we use to estimate the impact of improved energy efficiency. We then reaggregate the components of energy use in a way that allows us to separate the effects of changes in energy intensities from other factors that may have affected energy use significantly.

Meyers (40) presented a comprehensive summary of time series data showing energy use by fuel (including wood); fuel choices for space heating, water heating, and cooking; housing and household characteristics; weather; and other features of the residential sector. Using these data and our estimates of how much of each fuel is used for each purpose, we obtain the estimates of useful residential energy use per dwelling shown in Figure 13. By our measure of useful energy, delivered quantities of oil and gas are counted at 66% efficiency, solids at 55%, and electricity at 100% to account for differences in the utilization efficiencies of the various fuels at the point of end use. We have adjusted yearly data for variations in temperature (41). By 1987, delivered energy use per dwelling had fallen by 24% relative to 1973, useful energy per dwelling had fallen 22%, and primary energy use per household or occupied dwelling was 14% below its 1973 value. These declines suggest significant conservation of fuels and electricity.

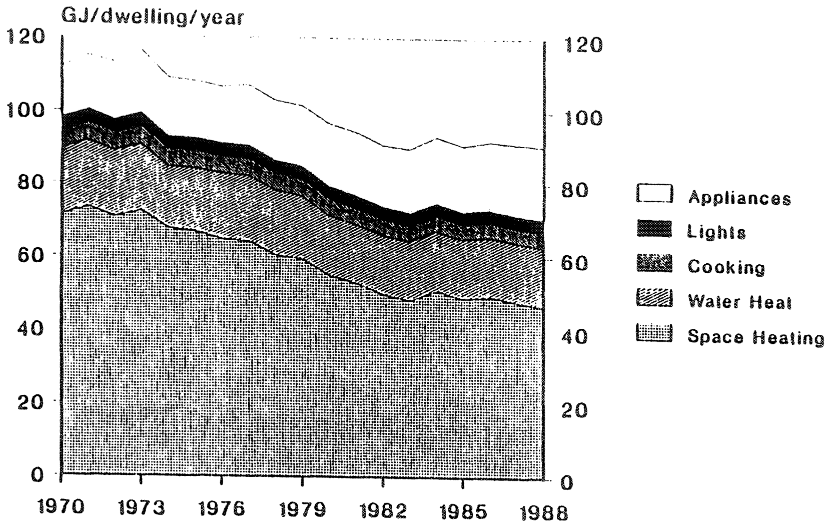


Figure 13 Residential energy use. Useful energy per household by end use, adjusted to normal weather. Useful energy is calculated by counting liquid and gaseous fuels at 66% efficiency and solids at 55% to account for conversion efficiencies of different fuels.

The Structure of the Residential Sector

Between 1973 and 1987, important changes in the characteristics of US homes occurred. While the penetration of central heating (here defined as the presence of a furnace or boiler circulating hot air or water through the home, a central heat pump, electric furnace, or built-in baseboard electric heating) increased slowly over the period to around 80%, the average heated floor area increased from 130 m^2 to nearly 140 m^2, which boosted space heating and lighting requirements in an approximately proportional fashion. Cooking and water heating equipment was virtually saturated in 1973. The ownership of major appliances (refrigerators, freezers, washers, dryers, air conditioners, and dishwashers), in number of units weighted by 1973 unit energy utilization of each unit, increased by 28% over the period.

Other important changes took place in the characteristics of households and homes. First, household size declined from 3.06 persons per household in 1973 to 2.72 in 1987. Schipper et al (42) suggested that energy use per household at a given time varies approximately with the square root of household size. For the parameters presented above, energy use per household should have declined by about 6%. But the decline in household size can be viewed as an increase in the number of households per capita of 13%. Thus the decline in household size leads to an overall increase in energy use per capita of approximately 6.5%. Second, the regional distribution of homes

shifted slightly, such that the average number of heating degree-days declined by nearly 3% between 1970 and 1980 (40). This decreased space heating requirements but increased cooling needs. On balance the geographical shift should have decreased delivered energy use by about 2%, a small effect.

Household activity, as measured by population, increased energy use by 15%. The structural factors outlined above together increased final energy use by 20%, primary energy by 26%. The total increase in primary energy use driven by changes in the level and structure of residential activity should have been 45%, slightly greater than that of the GNP. As it turns out, household energy use was restrained considerably by improved efficiency, as we show below.

Fuel Mix

During the 1970s and 1980s, major changes occurred in the mix of fuels used in US homes, as Figure 12 implies. Changes occurred for two reasons. First, existing homes switched from oil to gas and wood in space heating, from oil to electricity in water heating, and from gas to electricity for cooking. The switch in space heating was particularly rapid between 1978 and 1985, when more than 5 million homes switched away from oil heating (Figure 14) (43). Second, builders chose a significantly different mix of fuels for new homes than that of the existing stock. Gas and electricity are used in preference to oil

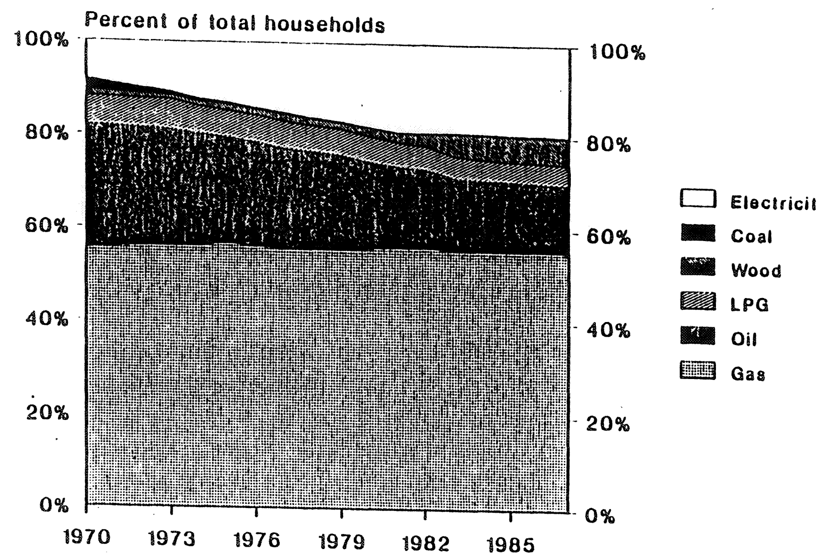


Figure 14 Principal household heating fuels. Share of homes using the indicated fuel as the principal space heating fuel. Sources: Meyers, RECS, US Census Bureau

in new-home space heating, and the share of electricity for space and water heating is much higher in new construction—around 50%—than in existing homes. By the second half of the 1980s, the shares of electricity in these substitutable applications levelled off, with only the higher share in new construction slowly driving up the total share. In the period 1973–1987, these two kinds of substitution had had roughly equal impacts on fuel choice.

Indeed, part of the decline in delivered energy per household occurred because electricity assumed a larger role in substitutable end uses, eliminating the on-site combustion losses that arise when fossil fuels are employed. Similarly, some of the increase in primary energy use per household occurred because more electricity-using devices were employed. Increases in appliance ownership increased the share of electricity in delivered energy, accounting for two-thirds of the increase in electricity use. These changes mean that aggregate household energy intensity, either on a primary or delivered basis, has limited utility as an indicator of the impact of improved energy efficiency.

We can estimate the impact of shifts in the fuel mix on residential energy use by asking how much fuel and electricity would have been consumed if the share of homes using electricity for space heating, cooking, and heating water in 1987 had been the same as in 1973, but other parameters (the number of homes and the unit consumption of energy-using equipment) had their 1987 values. Under these circumstances, about 0.3 EJ less site electricity would have been consumed, but about 0.97 EJ more fuel. Thus, the increase in primary energy use from this electricity substitution, about 0.95 EJ, was just about offset by the reduction in fuel use of 0.97 EJ. Note again that only part of these shifts occurred through the switching of fuels in existing homes.

Intensity and Efficiency: The Major End Uses

This section analyzes the end uses shown in Figure 13. Useful energy intensities for space heating (in kJ/degree-day/m^2) and major appliances (in kWh/appliance/yr) in 1987 were significantly lower than they were in 1973. Energy intensities of fuel-based cooking and water heating fell significantly, but those for electricity fell less. US homes would have used 39% more fuel and 15% more electricity in 1987 for all purposes than they actually did if these reductions had not taken place. This section reviews these changes.

SPACE HEATING Changes in space heating energy intensity have been dramatic. Weather-adjusted space heating fuel use in 1973 was approximately 7.1 EJ, electricity use 0.2 EJ. By 1987 fuel use fell to slightly under 6 EJ, while electricity use rose to 0.36 EJ. At the same time, the amount of heated floor area increased by nearly 40%. When consumption of principal fuels, as well as LPG and other solids is aggregated, useful energy per dwelling for space heating fell 34%, and 38% per unit of dwelling area. While some of the

decline in space heating fuel use was caused by lower home utilization or increased contributions to heating needs by waste heat from other end uses, the changes indicate significant conservation of energy.

Detailed examination of individual heating fuels supports this finding. According to our own tabulations, average consumption of gas in a home using gas for space heating fell by 35% between 1973 and 1987 vs 40% for oil and 26% for electricity. Data from the oil and gas industries (44, 45) show similar declines in sales of fuels for heating, as Figure 15 shows.

There are many causes for these reductions. The thermal characteristics of the external shells of existing homes were upgraded. The number of households adding insulation or other conservation features in 1987 kept pace with or increased slightly relative to earlier years (40, 43). New heating equipment was more efficient than older, too. According to data compiled by the Gas Appliance Manufacturer's Association, the efficiency of new gas furnaces increased from 63.2% in 1972 to 74.7% in 1988. The seasonal coefficient of performance of new heat pumps increased from 2.1 to 2.9 between 1978 and 1988. The gradual replacement of heating equipment in existing homes and installation in new homes has thus contributed to reducing energy use for heating. The share of heat pumps has reached 25% of new homes heated with electricity. Note, too, that part of the reduction in the use of the main space heating fuels, particularly oil, was permitted by a dramatic increase in the use of wood as a secondary fuel.

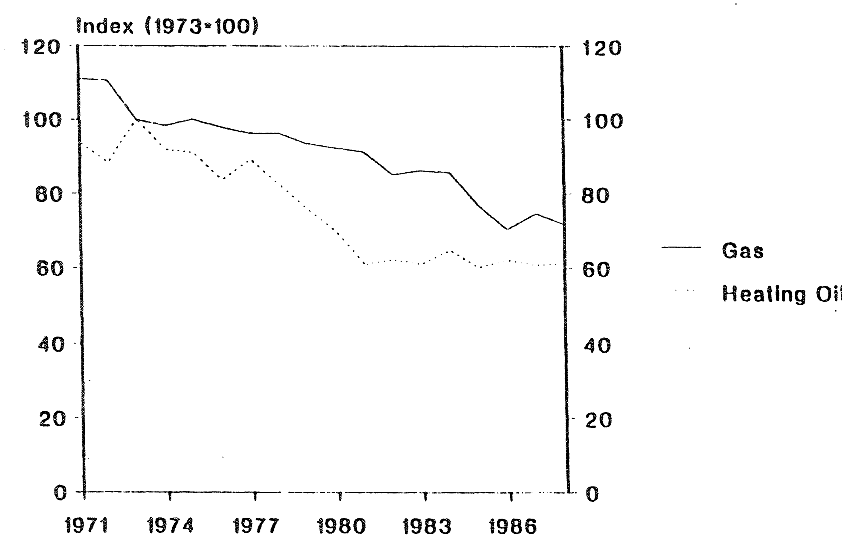


Figure 15 Residential sector. Indices of space heating fuel per dwelling. Sources: oil—*Heating Oil Magazine* yearly survey; gas—surveys from US Gas Association

Efficiency improvements of the building shell in new construction are equally impressive. Meyers (40) compared insulation levels in homes built in 1986 with those built in 1973. The improvement in the nominal thermal resistance of attic insulation was nearly twofold, from R14.4 (or $k = 0.39$ W/deg-C/m^2 in terms of thermal transmissivity) in 1973 to R26.8 ($k = 0.21$) in 1986, and that for wall insulation was less, from R10.0 ($k = 0.56$) to R12.5 ($k = 0.45$). The share of new homes with double- or triple-glazed windows increased from 40% to 79%. In a 1987 snapshot, the fraction of homes with storm windows, wall insulation, and insulated floors over a basement or crawl space is significantly higher in homes built after 1974 than that in homes built before 1974, confirming the new-construction insulation statistics. Similarly, heating equipment efficiency has also improved, as noted above. So energy use for heating in new homes should be significantly lower than that in existing homes.

Data on energy use bear out these improvements in equipment and building shells. Viewed in 1987, gas-heated homes built after 1974 used 20% less gas, as measured in MJ/degree-day/m^2 than those built between 1960 and 1974 (43). Evidently, even though gas heating intensity in these pre-1974 homes has fallen over time, this improvement has not closed the gap in intensity between new homes and the typical home built before 1973. Similar improvements apply to homes heated with electricity and fuel oil. Clearly new homes use less energy for space heating than older ones. Since 24% of the homes in 1987 were built in 1975 or later, this means that improvements in building practices have had an important impact on average heating intensity.

Not all of the reduction in space heating intensity was caused by improved technology, however. Thermostat settings in the early 1980s were several degrees lower than in 1973 (40). By 1987, settings were up slightly over 1984 (43). PNL (2) estimated that the contributions to the reduction in space heating energy intensity between 1973 and 1986 from better equipment and from better building shells in both existing and new homes were about one third larger than the "behavioral" component. Nevertheless, most of the reduction since 1973 is permanent. Only a very concerted effort to induce the raising of thermostat settings well above their 1973 levels would bring heating intensity close to its 1973 value.

WATER HEATING AND COOKING The principal fuels for water heating and cooking are electricity and natural gas, although oil is in some cases still used for water heating, and LPG is used for cooking and water heating in 10–15% of all homes. From 1973 to 1985, the efficiency of new gas water heaters increased only slightly from 47% to 51%, while new electric water heaters improved by a similar fraction. Automatic ignition (i.e. removal of pilot lights) on new gas stoves and clothes dryers has reduced standby losses.

Water use in washing appliances declined significantly, according to figures for dish- and clothes-washers that heat their own water.

It is difficult, however, to determine the changes in actual water heating and cooking energy use caused by improved efficiency. This is because behavior and utilization patterns cause significant changes in estimated or metered end use. Reduced household size, for example, has led to significant declines in hot water use per household; changes in eating patterns as well as additional use of microwave ovens led to lower unit consumption of gas or electricity, for cooking.

ELECTRIC APPLIANCES AND LIGHTING Although electricity use for lighting and electric appliances is not well documented (46, 47), estimates of aggregate electricity use per household for the six most important appliances (refrigerators, freezers, washers and dryers, dishwashers, and air conditioners) give some perspective on the changes that have occurred. Increased ownership of these appliances, had there been no change in unit consumption, would have boosted energy use for these six applications from about 3520 kWh per household in 1973 to about 4250 kWh per household in 1987. Instead, actual use was approximately 3750 kWh per household, representing a savings of approximately 12%, or 0.16 EJ.[10] If this savings rate were applied to all appliances (i.e. all electricity use excluding that for space and water heating and cooking), savings would be about 0.25 EJ.

A variety of studies document the improvements in the efficiency of new appliances sold since 1972 by weighting sales of each product by an indicator of efficiency.[11] Some of these improvements are shown in Figure 16. The improvements are greatest for refrigerators and freezers, smallest for electric water heaters. In general, the improvements are impressive, although further improvements are practical and economic (48).

The reductions in the average electricity consumption of the appliance stock between 1973 and 1986 are less than the improvements in new models, of course, because the turnover in the appliance stock is slow. Moreover, new appliances tend to have more energy-intensive features than appliances being retired (e.g. automatic icemakers in refrigerators). On the other hand, top-of-the-line models often have more energy saving features than simpler models. And average new freezer size declined between 1972 and 1988, while new refrigerator size remained constant after 1978. Finally, there are uncertainties in the estimates of in-home consumption vs laboratory consumption tests of

[10] The unit consumption figures were taken from the Lawrence Berkeley Laboratory Residential Model (J. MacMahon, private communication). The estimated electricity consumption per household for lighting shows a slight decline that can be explained by lower house occupancy (i.e. fewer hours spent at home) and smaller household size.

[11] In the case of refrigerators, for example, this indicator is given by volume per unit of yearly electricity consumption.

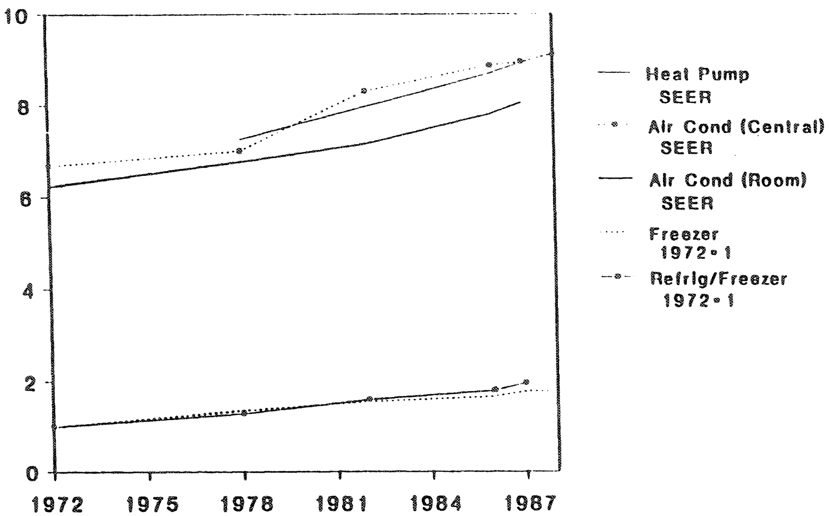


Figure 16 Appliance efficiency trends. Changes in efficiency ratios. These are the shipment-weighted efficiency factors for new electric appliances sold in the United States between 1972 and 1987. For each appliance shown, we display the seasonal energy efficiency ratio (SEER, cooling or heating per unit of electricity consumed) or efficiency (volume cooled per unit of electricity consumption) of all models shipped in the United States in a given year. Source: derived from ACEEE

new models. Thus the 12% reduction in stock-wide unit consumption that we cite represents the combined impact of efficiency improvements and all other factors.

What were the efficiency improvements? Refrigerator insulation, seals, motors, and compressors were improved. Air conditioner motors, compressors, and controls were upgraded. Water requirements for dish- and clothes-washers were reduced. Sensors were added to dryers to shut off heat and power when the moisture in the clothes was low enough. The savings were all achieved using low-cost technology (48).

There is still considerable room for reductions in appliance energy intensity. The average unit consumption of new appliances sold is well above the levels achieved by the most efficient models, and advanced prototypes are even more efficient. It is therefore clear that the present average new intensities do not represent the technically feasible limits of efficiency. And as many argue, these models are also far from limits of economic feasibility (47).

Conclusions: Energy Efficiency in the Residential Sector

The development of energy use in the residential sector is shown in Figure 17. Improved energy efficiency had a clear impact on the residential sector between 1973 and 1987. If only the intensity of fuel and electricity use had

changed while fuel shares, activity, and structural parameters had remained constant at their 1973 values, US homes would have used 6.7 EJ of fuel and 1.8 EJ of electricity in 1987, declines of 27% and 12% respectively from 1973 values. Put another way, reduced intensities alone cut total primary energy use by 21%. Alternatively, had the intensities of each end-use been frozen at their 1973 values, then fuel use in 1987 would have been 10.9 EJ and electricity use 3.6 EJ, yielding total primary energy use of 22.0 EJ, more than 5.7 EJ higher than actual.

Outlook

The energy intensity of a typical new house, heating system, or appliance is by no measure near its theoretical or even economic minimum. Indeed, comparison of average new electric appliance energy intensity with the lowest on the market shows a wide gap. But in some cases the rate of decline in intensity of most new systems has slowed or stopped. It appears that insulation levels in new homes built in 1986 and 1987 were no better than those installed in 1985. The slowdown in efficiency improvements represents a market slowdown, not a bottoming out of technology that is economically attractive (49). The outlook for further decline is therefore dependent on

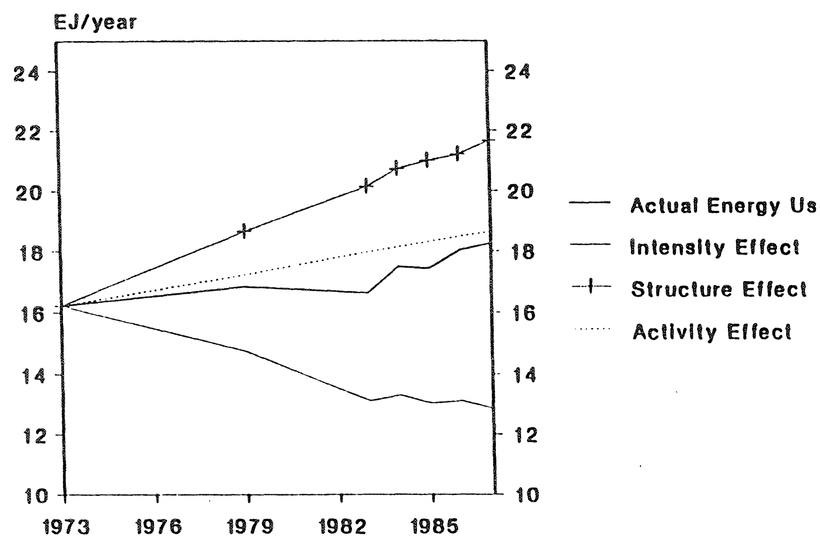


Figure 17 Residential primary energy use. Intensity, activity, structure effects. Evolution of actual and hypothetical primary energy use in the residential sector. Each "effect" is computed by having only intensity, activity, or structure (as defined in the text) follow its actual path while holding the other two components at 1973 levels.

future forces that affect the marketplace—residential energy prices, the perceived or real incremental benefit of greater efficiency, and public policy.

One important policy that will raise efficiencies is the National Appliance Efficiency Standards, which take effect initially for refrigerators, freezers, water heaters, and room air conditioners in 1990. More stringent efficiency requirements for refrigerators and freezers will take effect in 1993, and requirements for other products are likely to be upgraded in the future as well. California, one of the largest economies in the world, has upgraded its own requirements on the efficiency of household appliances sold in the State, too. This type of policy circumvents consumers', manufacturers', and builders' high implicit discount rates, as well as a variety of other market and nonmarket barriers to more efficient energy use.

Moreover, there are a number of important energy-saving technologies that are starting to penetrate the market to a significant degree (18, 49). These include low-emissivity glass for windows, vastly improved gas furnaces and gas heat pumps, and electric heat-pump water heaters. As for the future of very efficient refrigerators, freezers, and air conditioners, progress here is clouded by uncertainties over future refrigerants (50). Finally, novel wall constructions and building techniques, as practiced almost universally in Sweden (51), promise to reduce heating losses in new detached housing markedly. A further decline in energy intensity should occur as these new technologies are more widely disseminated, as ongoing R&D leads to ever better technologies (such as gas-fired heat pumps), and as appliance and building standards take effect and are improved.

SERVICE SECTOR

The energy use of the service sector is dominated by building-related activities (52). Survey data on energy use, floor area, and other characteristics of the US service sector are available only for 1979, 1983, and 1986 (53). From other data (SEDS) (54), which include energy use for activities not associated with building energy use, Schipper et al (52) assembled a time series of energy use data that can be adjusted to match the 1979 and 1983 surveys. The results for key years are shown in Figure 18. Delivered energy use rose from 5.3 EJ in 1973 to 5.9 EJ in 1979—a very cold year, then fell to a plateau of 5.3 EJ in 1986. Primary energy use, on the other hand, rose from 8.8 EJ in 1973 to 11.1 EJ in 1986, as a result of the substitution of electricity for fuels and further penetration of electricity-driven services like computers and lighting.

The Structure of the Service Sector

Service sector GNP, excluding utilities, grew nearly 50%, from 1.67 trillion dollars in 1973 to 2.51 trillion in 1987 as evaluated at 1982 prices. We take

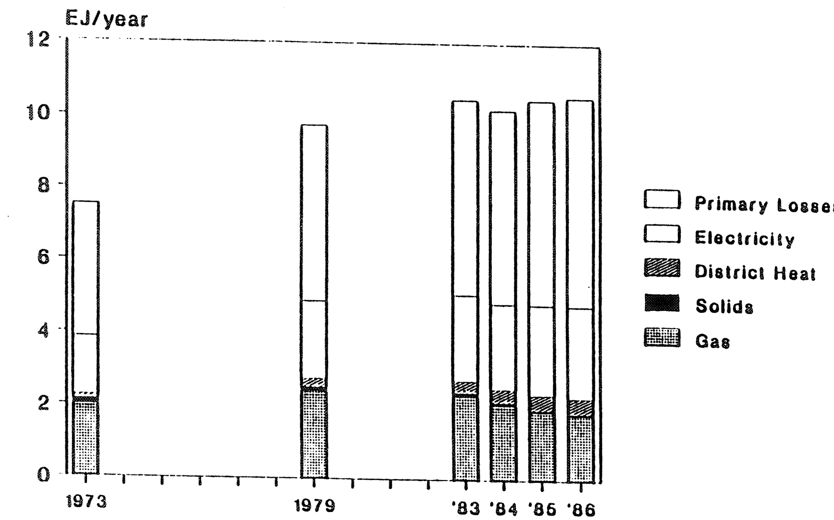


Figure 18 Energy use in service sector buildings by fuel type. Sources: SEDS, NBECS.

these figures as the indicators of the change in sectoral activity over the period of the analysis. The structure of the service sector can be measured by several quantities. The most important is floor area, which grew from an estimated 3.5 billion square meters in 1973 (52) to more than 5.4 billion square meters in 1987 (53). This growth was only slightly faster than the growth in service sector GNP. However, the ratio of sectoral floor area to total GNP increased because the share of service sector GNP in overall GNP increased from 61% to 65%.

Additionally, the mix of buildings changed slightly. According to PNL (2), the share of office building floor space increased from 16.6% in 1972 to 19.8% in 1986, and shares of warehouses and lodging increased slightly. Shares of retail, food sales, and educational floor space fell, the latter significantly, from 16.1% to 13.9%. And the geographical distribution of buildings shifted slightly towards the South and West. According to PNL, the mix effect increased fuel and electricity use by about 0.08 and 0.06 EJ, respectively, while the geographical shift reduced fuel needs by 0.04 EJ but increased electricity use by 0.02 EJ. Thus the impact of structural change, as measured by the slight increase in the floor area per unit of service sector GNP, changes in the mix of buildings, and geographical shifts, is very small compared to total fuel utilization of 2.5 EJ and electricity use of 2.5 EJ in 1986. By contrast, the activity effect was significant because the service sector GNP grew 7% more than total GNP. Yet between 1973 and 1987, service sector energy use increased by only 5%, while primary energy use grew by 27%.

The structural change reported here does not include shifts in the kinds of energy services provided in buildings, particularly those relying on electricity. The share of floor space provided with cooling, and the level of use of computers and other communications equipment has increased markedly. These shifts increased electricity use. Some of the waste heat from this electricity use reduced space heating needs in winter months but increased cooling needs during the rest of the year. Hence a broader view suggests that the overall impact of structural change on energy use in the service sector has reduced fuel use slightly for heating but increased electricity use significantly for a variety of purposes.

Fuel Mix

The mix of fuels in the service sector has evolved in a manner similar to that of the residential sector, away from oil and towards electricity. Driving the increased share of electricity was both further electrification (i.e. more uses of electricity), as well as greater penetration of electric heating. Measured by the area of buildings they heated, heating fuels chosen were predominantly oil (22%) or gas (50%) in 1979.[12] From NBECS data on heating fuels in buildings built before 1973 we infer that the share of area heated by electricity grew steadily, from, approximately 7% of the entire stock in 1973 to 15% in 1979 and 21.5% in 1986, while those of gas or oil (and LPG) have decreased from an estimated 87% in 1973 to 67% in 1986. Part of this shift towards electricity as the principal heating fuel is explained by the shift of service sector activity towards warmer climates, where lower heating loads permit electric heating to compete better against gas or oil.

Intensity and Efficiency

Measuring changes in energy efficiency requires the disaggregation of energy use into end-uses, such as space heating or cooling. But the services provided by energy in the service sector are diverse and changing. With current data gathering efforts, it is very difficult to break energy use by fuel into end uses, and it is therefore very difficult to derive energy intensities for each purpose in order to gauge the impact of improved efficiency.

It is possible, however, to estimate how energy use per unit of floor area has changed. Since surveys have measured energy use and intensity only since 1979, comparing present-day intensities with those from 1973 is problematic. The imprecision of the SEDS (54) data compound this problem.

[12] NBECS (53) did not distinguish between primary and secondary heating fuels. We took the share of buildings using each fuel over the sum of the shares, which was 114%.

Nevertheless, Schipper et al (52) found a 16% decline in delivered energy use per unit of floor area between 1973 and 1983; extending the data from that report to 1986 (to compare with NBECS) and extrapolating to 1987 yields an overall reduction of 33%. The intensity of fuel use, including district heat, fell 49%. About half of this decline was likely caused by reductions in the proportion of floor area heated by fossil fuels and by the very mild winter of 1987. We can compare energy intensity in 1979 and 1986 by building type. Figure 19 shows that delivered energy per unit floor area declined for most building types. The same is true for fuel intensity, electric intensity, and primary energy intensity.

Most fuel is used for space heating, with a small amount of fuel used for water heating and cooking (55). Most observers allocate as much as 80% of fuel use to space heating. We believe, therefore, that comparing fuel (and district heating) use to the estimated area heated by fuel provides one meaningful measure of energy intensity. By our estimate, heating intensity lay at 940 MJ/m^2 in 1973, falling to 790 MJ/m^2 in 1979 and further to 560 MJ/m^2 in 1986. Even allowing for uncertainties in weather correction, the share of fuel used for heating, and the share of buildings with fuel heat in 1973, the magnitude of this change is a clear indication of significant savings of space heating fuel.

Some more precise measures of intensity changes are available from NBECS. Gas use per unit area in buildings heated with gas, for example, was 981 MJ/m^2 in 1979 as compared with 555 MJ/m^2 in 1986. Although use of

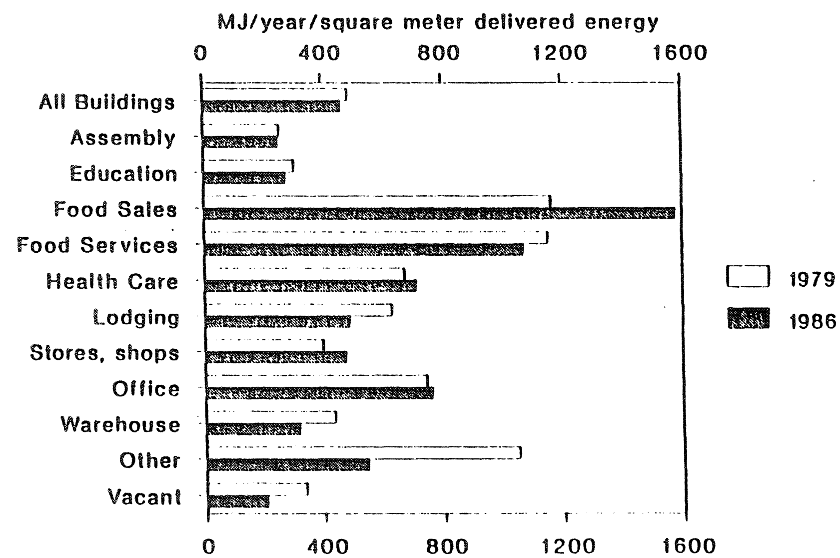


Figure 19 Service sector. Changes in energy intensity by subsector. Source: Ref. 53

secondary fuels may account for part of this drop, increased efficiency is evident. Figures for oil heat show a similar decline. The fuel intensity of most building types also fell between 1979 and 1986. Since most fuel was used for space heat, this evidence points towards a significant savings of space heating.

Electricity is more problematic, because the only use found in every building is that for lighting. Available data do not permit a comparison of electricity use by end-use over time. Electricity intensity in buildings that heat with electricity fell from 650 MJ/m^2 in 1979 to 579 MJ/m^2 in 1986, about the same percentage reduction as the change in the number of heating degree-days. Thus it is difficult to draw conclusions about the intensity of electric heating. The same applies to cooling. On the other hand, total electricity intensity, aggregated over all buildings, remained constant between 1979 and 1986. Since the penetration of electric heating, cooling, and other equipment (e.g. computers) increased, this implies that some improvements in the efficiency of electricity utilization must have occurred.

Combining the limited knowledge we have concerning the use of individual fuels suggests that the reduction in fuel intensity between 1979 and 1986—almost 37%—was caused principally by efficiency improvements, but increased penetration of electric heating captured about 5% of the heated floor area between 1979 and 1986, and the milder climate in 1986 alone allowed a reduction in heating needs of about 10%. The remaining decline, approximately 25%, can be ascribed to saved fuel for space and water heating.

The PNL analysis (2) attempted to quantify the factors that caused intensity to fall. Although it found more than 80% of its "conservation" effect unexplained, it judged that factors other than improvements in building shells accounted for much of the savings. Building shell retrofits accounted for 7% of the savings, and the high efficiency of new buildings relative to the existing building stock for an additional 8.5%. The location of more buildings in warmer climates had a minor effect. A shift in building type also contributed to the decline in fuel use. PNL, on the other hand, omitted explicit reference to the shift towards electricity as a primary and secondary heating source. Our estimate of the share of electric heating in 1973, 7%, implies a loss of more than 14 points in the share of fossil-fuel heating, which by 1986 should have reduced fossil fuel intensity over all buildings by nearly 10%, accounting for part of PNL's unexplained residual. We estimate that whereas only 0.1 EJ of electricity was used for heating in 1973, the figure increased to 0.32 EJ in 1986; cooling electricity use increased from 0.27 EJ in 1973 to 0.42 EJ in 1986.

Conclusion: Energy Efficiency in the Service Sector

How much energy was saved in the service sector between 1973 and 1987? We showed that relative to overall GNP, service sector GNP and total

building area increased slightly, increasing sectoral energy use. Fuel shift reduced fuel needs but increased needs for electricity. Although our figure are rough, we believe that a 40% decline in fuel heating intensity and an 18% decline in electric heating intensity took place. These improvements yielde savings of approximately 1.5 EJ of fuel and 0.07 EJ of electricity, a compared with actual utilization of 2.16 EJ and 0.33 EJ, respectively. Finally, the increased share of electric heating raised electricity use by approximately 0.15 EJ but reduced fossil fuel use by roughly 0.6 EJ.

Outlook

A number of studies (18, 49, 55, 56) suggest that the intensity of virtually an new system or energy service can vary considerably. New lighting systems supported by specular reflectors, electronic ballasts, and judicious use o daylighting, have reduced electricity intensity for lighting by 50–75% in som commercial buildings (55). Low-emissivity glass can reduce heat losses o gains significantly, yet allow for maximum use of daylight to reduce artificia lighting loads as well. Variable speed/volume space-conditioning system offer reductions in power for motors and compressors without reducin comfort; air-to-air heat-exchangers allow for higher indoor air quality wit substantial heat-loss reductions. Interestingly enough, the trend towards des ignated smoking areas could also lead to a reduction in ventilation needs, a smoke-free areas require far fewer air exchanges than areas where smokin takes place.

National surveys as well as information from equipment manufacture indicate that various energy-saving technologies are starting to be adopted o a large scale. For example, the national survey of commercial building conducted by the US Department of Energy showed that high-efficienc ballasts had been implemented in 42% of new commercial floor space delamping programs had been implemented in 21% of commercial floo space, and energy management and control systems had been implemented i 19% of commercial floor space as of 1986 (53). These and other technologic improvements contributed to the decline in energy use per unit of floor are during 1973–1986.

Continuing technological improvements in lighting, space conditionin and other end-uses will limit future growth in energy use in the service secto These improvements are being stimulated by market forces as well as goven ment and utility programs. For example, the federal government adopte minimum efficiency standards for new fluorescent lighting ballasts. The standards, which took effect January 1, 1990, are expected by the year 20(to reduce electricity utilization in commercial buildings by around 0.1 EJ/ (equivalent to 4% of electricity use in commercial buildings in 1988 (57 Minimum efficiency standards for fluorescent and incandescent lamps a being adopted in Massachusetts (58), and lamp efficiency standards are under consideration in other states as well as at the federal level.

In 1989, the US Department of Energy issued minimum efficiency standards for new commercial buildings (59). These standards are mandatory for federally owned buildings but voluntary for the private sector. States that follow these guidelines by revising their building codes could significantly reduce energy use in the services sector over the long run. For example, models suggest that new office buildings meeting these standards would use 15–30% less primary energy than buildings complying with standards widely adopted in the early 1980s (55).

Concerning utility programs, many utilities provide financial incentives such as rebates to stimulate the adoption of energy-efficient technologies in the service sector. A few utilities even install energy-efficiency measures at their own expense on the premises of their customers. The most effective utility programs are reaching 70% or more of eligible customers and are reducing electricity use by 10–30%, although most utility programs are not nearly this successful (60). The overall impact of utility energy-efficiency programs is expected to grow as more utilities implement full-scale programs, programs are improved, and the goal of "least-cost energy services" spreads throughout the utility industry.

One technological trend—the proliferation of electronic office equipment—could significantly increase future energy use in the services sector. Saturation of personal computers, printers, copiers, fax machines, etc is expected to continue growing during the 1990s. One study estimates that without efficiency improvements, total electricity use by office electronic equipment could climb by 160–360% between 1988 and 1995 (61). However, full use of today's most efficient hardware could potentially eliminate all of this electricity demand growth. Thus, with uncertainty regarding both the rate of growth and the efficiency of new electronic equipment, it is difficult to predict future energy use in the services sector.

CONCLUSIONS AND DISCUSSION

The Impacts of Improved Efficiency

Figure 20 shows the evolution of primary energy use from 1973 to 1987 (see also Table 1). We give actual primary energy use measured for the sectors we have considered,[13] and the three hypothetical levels of primary energy use

[13]We omit consideration of the residual between total primary energy use as reported by DOE (5) and the primary energy used in the sectors considered in this analysis. It is unlikely that the evolution of the residual between our figures and those given by DOE—from 12.6 EJ in 1973 to approximately 11.6 EJ in 1987—has an important impact on our results.

that would obtain if only energy intensities, only sectoral activity levels, or only intrasectoral structure had changed over time while the other two factors were held constant at their base-year (1973) values. The impact of changing energy intensity is almost equal and opposite to that of activity, while structural change led to modest increases in energy use. Thus reduced energy intensities had a major impact on US primary energy use.

Figure 21 summarizes the impacts of structural changes on US energy use by sector between 1973 and 1987. All figures are indexed relative to their 1973 values. It can be seen that only in the service and manufacturing sectors did sectoral activity grow more rapidly than GNP. Intrasectoral structural change, on the other hand, placed substantial upward pressure on residential energy use; had relatively small effects in the service, freight, and passenger transport sectors; and yielded significant energy savings in manufacturing. Taken together, the impacts of changes in both activity and structure exerted a small upward influence on energy use relative to GNP in the residential and service sectors and a small downward influence in the freight, passenger transportation, and manufacturing sectors. In the aggregate, increased activity levels and structural change would have increased delivered and primary energy use by 35%. Actual energy use, on the other hand, decreased by 2% in terms of delivered energy, and increased by only 6% in terms of primary

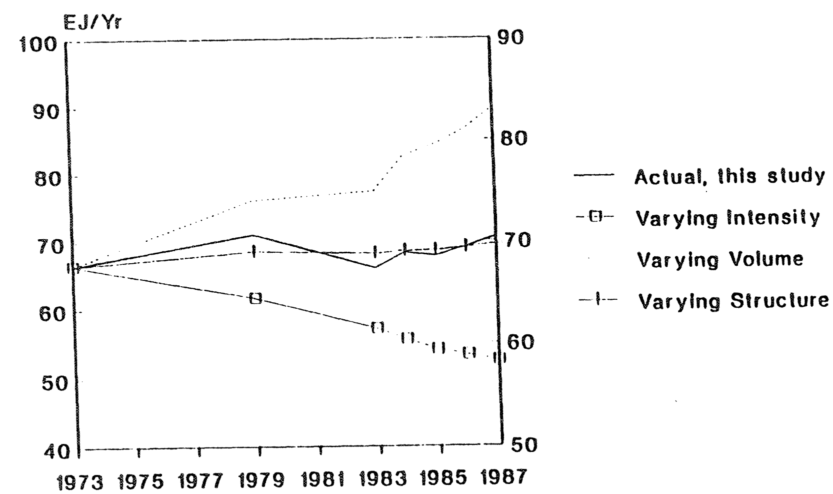
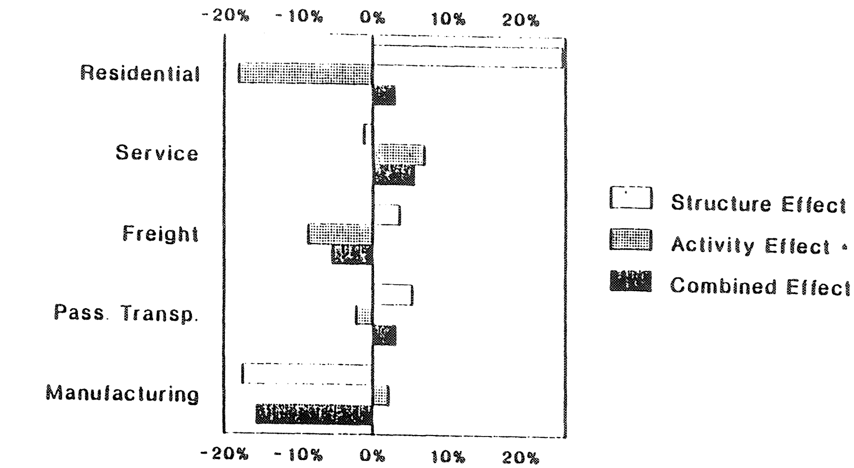


Figure 20 Primary energy use. Evolution of actual and hypothetical energy use in the five-sector aggregate. Each "effect" is computed by having only intensities, activity levels, or structure (as defined in the specific sectors) follow its actual path while holding the other two components constant at 1973 levels. Definitions of these components are given in the respective chapters. Fuel and electricity figures from each activity sector are summed counting electricity being at 11,500 Btu or 12616 kJ per kWh to account for conversion losses. Sources: DOE, LBL



* Activity is normalized by GDP

Figure 21 Changes in delivered energy use since 1973. Activity and structure effects. Hypothetical 1973–1987 changes in energy use if only sectoral activity level per unit of GNP (activity effect) or the composition of activities as defined in the respective sectors (structure effect) had followed their actual paths while all other factors had remained constant at 1973 levels. The net effect captures the combined impact of changes in the mix and level of activities in each sector relative to GNP.

energy. In either case, the divergence between the two sets of figures is an indication of the substantial impacts of improved efficiency on US energy use.

Which sectors showed the greatest reductions in energy intensity? Figure 22 shows how structure-adjusted energy intensity, in terms of both delivered and primary energy, evolved over time in each end-use sector. The declines varied from 31% in manufacturing to 20% in passenger transportation to 4.5% for freight. (In primary terms, the percentage declines were less except for transport, where they were the same.) These declines together point to a reduction in aggregate energy intensity between 1973 and 1987 of the sectors considered in this report of 24% in terms of delivered energy or 21% in terms of primary energy. These improvements correspond to net savings of 16.5 EJ of delivered energy and 19.7 EJ of primary energy at 1987 activity levels. That delivered energy intensity fell more than primary reflects the fact that fuel intensity fell by 26% while electricity intensity fell by only 8%.

We can also highlight the activities where the most unambiguous efficiency improvements occurred: passenger air travel energy intensity declined by nearly 50%, residential and services space heating intensity by about 35%, and manufacturing fuel intensity by about 34%. Automobile and light truck vehicle fuel intensity fell by 28%, but falling load factors offset this improve-

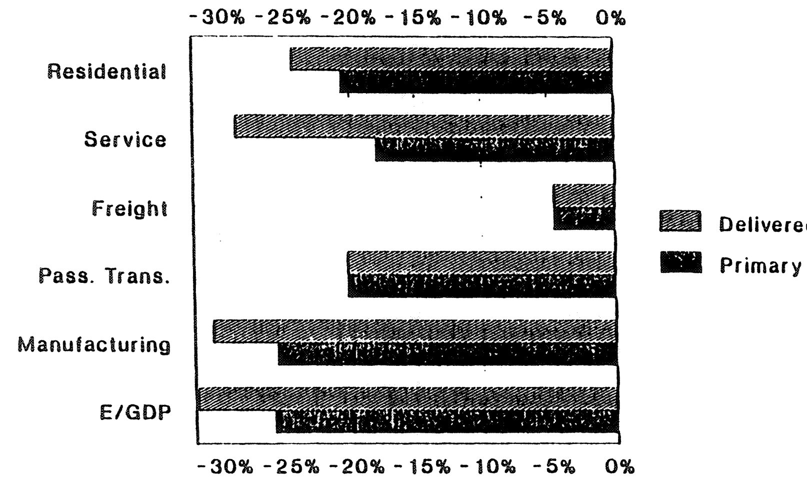


Figure 22 Changes in delivered energy use since 1973. Energy intensity effect. Hypothetic 1973–1987 changes in primary and delivered energy use if only energy intensities had follow their actual paths while sectoral activity levels and structure had remained at 1973 levels.

ment in travel efficiency. The intensity of electric appliances declined b some 12%.

Several factors served to increase energy demand, thereby offsetting in pa the impact of these improvements. Truck freight intensity increased, in pa because of the rise in short-haul light trucking. Changes in the modal mix passenger transportation raised energy use slightly. Heated residential flo area, and the number of appliances per household, increased. Changes in t kinds of services offered in commercial buildings, particularly those usi electricity, raised energy use. Structural change in the manufacturing secto on the other hand, led to reductions in the production of energy-intensive bu materials relative to other products.

Since the energy/GNP ratio is sensitive to all factors affecting energy us not just those that are conceptually related to energy efficiency, it is misleading efficiency indicator to the extent that structure and activity ha important effects. On balance, structural change and growth in secto activity levels served to raise the level of energy use. But the growth in ener use induced by these factors was smaller than the increase in GNP, so t changes in the level and structure of sectoral activities led to net reductions the energy/GNP ratio over the period of analysis. The reduction in the prim energy/GNP ratio between 1973 and 1987 therefore overstates the efficien improvement that occurred over the period, perhaps by as much as one-fou of the total reduction in the ratio.

The Efficiency Slowdown

Figures 20 and 22 show that improved energy efficiency had a considerable impact on total US primary energy use. Data from the last several years, however, suggest that the rate of efficiency improvement implied by our sectoral analyses may be slowing down or even coming to a halt. The drop in world oil prices in 1986 has begun to have an impact on energy intensities. The energy intensities of some classes of energy-using equipment, such as new automobiles, are no longer decreasing over time. In some applications, energy intensity is even increasing.

In the residential sector, primary and useful energy use per household declined through 1983 but have increased in more recent years. Heating intensity, which had fallen by 4.5% per year through 1983, fell by less than 1% per year between 1983 and 1987. Adjusted for structural change, primary energy intensity also fell more rapidly before 1983 than thereafter. By contrast, the rate of decline in appliance energy intensity increased after 1982, and should continue to fall because new appliances are more efficient than older ones.

In the service sector, the decline in fuel heating follows the same pattern as space heating in homes, while the increase in nonheating electricity intensity before 1983 turned to a decline after that time. Structure-adjusted primary energy intensity in services thus falls more rapidly after 1983 than before, although the decline appears to bottom-out after 1985. These observations suggest that efficiency increases in buildings have slowed, although the impact of more efficient electricity use is delayed as the impact of new equipment is still being felt in the stock.

The transportation sector shows an intensity plateau, too. The specific fuel utilization of personal vehicles fell more rapidly before 1983 than in more recent years. This is due to the rapid growth in light trucks during the late 1970s and early 1980s as well as the relaxation of federal fuel-economy standards in recent years. The combined fuel intensity of new cars and light trucks fell by 6.2% per year before 1983 but by only 1.3% per year thereafter. Passenger energy intensities as measured in MJ/passenger-km fell less rapidly because of the decline in load factors. Air passenger intensity fell more rapidly before 1983 than from 1983 to 1985, but the decline accelerated again after 1985. Significantly, the improvement in air and automobile passenger fuel intensities was most rapid during the period of rapid activity growth. This makes sense: growth in activity implies investment in newer, more efficient vehicles and higher load factors on planes. Together, these effects lower the average passenger intensity of the transportation sector. For freight, all indicators point to more rapid progress before 1983 than thereafter; the ORNL data, for example, show that no substantial improvements in truck fuel economy have been achieved since 1982.

In the manufacturing sector, on the other hand, there is less evidence of a slowdown in efficiency improvements. As in passenger transportation, manufacturing energy intensity is strongly dependent on changes in sectoral activity. Energy intensity, adjusted for structural change, increased at annual rates of 0.3% and 2.2% during the recession years 1980 and 1982. But in years with strong sectoral growth, energy intensity has fallen very rapidly. Between 1983 and 1985, for example, energy intensity fell at an average rate of 6.2% per year—more than twice the long-term average annual rate of 2.7%. These fluctuations are presumably caused by two factors. First, decreased capacity utilization during recessions leads to the inefficient use of energy inputs. Second, sectoral growth permits investment in new, relatively efficient technology. The response of manufacturing energy intensity to the drop in energy prices in 1986 is difficult to gauge in the absence of manufacturing energy use data past 1985. As we noted above, the aggregate energy intensity of the industrial sector, which is dominated largely by manufacturing, decreased by 2.9% between 1985 and 1986 but remained almost constant between 1986 and 1987. But energy-intensity statistics from the iron and steel, paper and pulp, and chemicals sectors indicate continuing reductions in energy intensity of 1.7 to 4.1% per year.

When we assemble a picture from each sector, the results are rather surprising. Structure-adjusted energy intensity fell by 2.35% per year after 1983, but only 1.8% before. For primary energy intensity, the figures are 2.0% and 1.5%. Significantly, however, intensity fell by only 1.7 and 1.5% between 1985 and 1987. Thus the overall impact of energy-efficiency improvements was most rapid between 1983 and 1985, a period of economic recovery and flat or declining real energy prices.

We have not discussed energy prices in detail in this review. It is worth noting that between 1973 and 1983, real prices for natural gas grew at average rates of 7.4% and 13.1% per year in the residential and industrial sectors, respectively, electricity prices grew by 2.3% per year in the residential sector and 5.7% per year in the industrial sector (5); and regular gasoline prices rose at an average rate of 8.6% per year. Between 1983 and 1987, however, all of these prices declined in real terms. Residential heating oil prices behaved similarly. That real prices were declining when intensity was falling the most rapidly seems counterintuitive. Yet we have suggested that time lags in the system, as well as the poor state of the economy in the early 1980s, retarded the replacement of inefficient equipment, and likely slowed investment to improve existing equipment as well. The effect of this improvement was swamped, however, by the dramatic crash in prices after 1986, although it is too early to judge the more long-term effects.

Implications for Future Energy Use

Are the energy savings that have been achieved over the past 15 years permanent? The rapid savings in space heating through 1983 may have been bolstered by short-term sacrifices that could wear off with lower prices. But the savings that accumulated after 1983 were likely achieved through technical improvements that are unlikely to be reversed in the near-term future. Savings in electricity use in the service sector also appear to be technologically based, and therefore not easily reversible. Savings in personal vehicles were almost totally due to technology, not reduced driving distances. Even if new-car fuel economy remains stable at its present value (27 to 28 mpg nominal, 22 to 23 mpg actual), it still lies 20% above the on-road fleet average. The savings in manufacturing may represent only the extension of a long-term trend, and therefore might be considered permanent.

At the same time, we must not overlook the implications of the slowdown in energy-efficiency improvements, which has appeared primarily in those sectors dominated by consumers: driving and household energy use, and services. Similarly, the rapid growth in the activity levels of the service and passenger transport sectors must be borne in mind. As Schipper et al (42) suggest, increases in free time could drive up energy uses for thes purposes, as well as for the private vehicle travel associated with out-of-home services. That is, a combination of the slackened improvement in efficiency indicated by the slowdown and continued growth in the volume of key end-uses—structural change—could propel energy uses upward once again.

A return to growth could pose significant policy problems in light of scientific concern over the role of fossil fuel combustion in global climate change (62). If efficiency improvements slow down while structural change increases energy demand further, then policy makers will have to work harder to restrain the emissions that result. If increased demand takes up the slack in world oil markets, the world's economies may see a repeat of the roller coaster of the 1970s and 1980s. Technological progress fostering a return to improved energy efficiency might head off one or both of these possible dilemmas. As Carlsmith et al (18) and Hirst (49) point out, the technical, economic, and policy opportunities are enormous. But as Schipper (63) warned, policies may have caused only a small increment in the total savings in the industrialized countries through 1985. Achieving the potential savings documented in the literature through the implementation of appropriate policies will be the challenge of the 1990s and beyond.

NOTE ADDED IN PROOF Preliminary analysis of yet unpublished data for 1988 indicates that fuel intensity, adjusted for structural change, fell by 6.0% (2.0% per year) between 1985 and 1988; electricity intensity fell by 10.8% (3.8% per year); and total energy intensity fell by 6.6% (2.3% per year). These results generally confirm the approximations used in this section.

ACKNOWLEDGMENTS

This work was carried out with the support of the US Environmenal Protection Agency and the US Department of Energy, as well as several private funding sources. We acknowledge the contributions of Stacy Davis of the Oak Ridge National Laboratory, who kindly provided much assistance in interpreting the ORNL transportation data, and Sarita Bartlett and Peter Duerr, who assisted in the preparation of these data. Steve Meyers made available to us detailed data on residential energy use and commented extensively on the manuscript. Finally, we acknowledge thoughtful comments by Arthur Rosenfeld, Marc Ross, and Rob Socolow.

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UNITED STATES ENERGY USE FROM 1973 TO 1987: THE IMPACTS OF IMPROVED EFFICIENCY

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1990

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Annu. Rev. Energy. 1990. 15:455–504

UNITED STATES ENERGY USE FROM 1973 TO 1987: THE IMPACTS OF IMPROVED EFFICIENCY[1]

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KEY WORDS: US energy efficiency, energy use and structural change, US energy demand since 1973, energy intensity, energy use trends.

INTRODUCTION

The purpose of this review is to investigate the evolution of energy demand in the United States since the early 1970s with the goal of measuring the impacts of improved energy efficiency. We examine the changes in final energy demand that were induced by changes in energy intensities, which are related to efficiency improvements; by changes in the aggregate activity levels in each major end-use sector; and by changes in the structure of activity within each sector. Where possible, we examine the changes in energy-efficiency trends caused by the drop in world oil prices in early 1986. Finally, we offer a view on prospects for enhanced energy efficiency over the long-term future.

Methodology

Studies of comparative energy efficiency often make use of aggregate indicators such as the ratio of primary energy use to Gross National Product

(GNP). But the use of energy/GNP ratios as efficiency indicators is suspect on both theoretical and empirical grounds. The energy/GNP ratio is determined not only by changes in the efficiency of energy utilization, but also by changes in the growth of energy-using activities relative to GNP. As a recent study of the Norwegian economy shows (1) the effects of structural change on energy-output ratios may be substantial.

In this study we follow a fundamentally different approach. We examine the evolution of energy use in each major end-use sector and relate the changes that occurred to the effects of three causal factors: (*a*) changes in the aggregate level of energy-using activities in each sector; (*b*) changes in the structure or composition of activities; and (*c*) changes in energy intensities, or energy use per unit of activity or output. Of these three factors, only energy intensity (actually its inverse) is conceptually related to energy efficiency. Our work builds on and extends similar analyses performed by the Pacific Northwest Laboratory (PNL) (2) and the US Department of Energy (DOE) (3).

Our approach is one of factorization. For each sector we measure changes in activity, structure, and intensity and calculate the change in energy use that would have occurred in response to each factor if the other two had remained constant at base-year (1973) values. We then compare the overall activity change in each sector with the change in GNP. Where fuel switching is important we estimate the energy use that would have occurred in 1987 if fuel choice shares of 1973 had remained constant. Where possible, we disaggregate energy use by fuel type to circumvent the difficulties involved in the selection of an aggregate energy index (4).

We then seek to measure the impact of improved energy efficiency on total energy use by comparing energy intensities in 1973 and 1987, noting the differences, separating out the effects of fuel substitution where possible, and then multiplying each difference by the corresponding level of affected activity in 1987. For example, automobiles and light trucks in the United States required approximately 6.35 MJ/vehicle-km in 1973, but only 4.3 MJ/vehicle-km in 1987. Since these vehicles were driven 2.7 trillion vehicle-km in 1987, efficiency improvements "saved" 5.5 EJ of fuel, or about two and one-half million barrels per day of oil equivalent. These "savings" show how much more energy would have been used had intensity not fallen. While energy intensities are not strict indicators of energy efficiency because they are determined in part by behavioral and structural factors—the energy intensity of steel manufacture may, for example, decline either because of improved process technologies or because of increases in the utilization of scrap metal—energy intensities are observable while technical efficiency generally is not.

We summarize our findings by noting how major activities grew or contracted within each sector, and whether measures of overall sectoral activity grew more or less rapidly than GNP. Similarly, we can index the changes in intensity we observe to see which were rapid and which were slow, with an eye to the changes in the energy/GNP ratio. From this analysis we can identify the most important causes of change in US energy use since 1973, and hence likely sources of change—upward or downward—in the future.

In this approach we do not attempt to assign behavioral causes to energy savings. Thus while we refer to changes in prices and incomes that doubtless had fundamental impacts on the evolution of structure, energy intensity, and fuel choice, we leave a formal treatment of the impact of these factors for another study. But we do identify the physical components of energy saving, such as greater load factors in air travel, or a shift to slightly smaller automobiles. And where possible we attempt to distinguish between change that is reversible and change that is essentially permanent.

Sectors, Time Frame, and Data Considered

We focus on five energy use sectors—passenger transport, freight transport, households, the service sector, and manufacturing—that together account for approximately 80% of end-use energy as measured by the Department of Energy (Figure 1) (5). Our time frame is 1973 to 1987, although we have studied manufacturing energy use back to 1958, residential energy use as far back as 1960, and transportation energy demand back to 1970. The approach requires a reasonably accurate disaggregation of the residential and service sectors. We disaggregate manufacturing energy use from that of other industry, including the mining, agriculture, and construction sectors, about which little is known in spite of the fact that they used some 5.3 EJ of energy in 1985. Unfortunately, the last year for which the manufacturing sector data are disaggregated is 1985. We use a bottom-up disaggregation of energy use and activity for passenger travel, omitting travel by school bus. But we do estimate the important impact of light trucks on total passenger travel. For freight, we have estimated the haulage by light trucks but ignored natural gas use in pipelines (about 0.7 EJ in 1987) because there is no measure of natural gas movements. In all we estimate that the many uncertainties in energy demand and activity levels are smaller than the most important changes that have occurred since 1973. Hence we believe our conclusions are robust.

Summary Findings

Our principal findings are (see Table 1):

1. Aggregate energy intensities in the residential, services, manufacturing, freight, and passenger transportation sectors, adjusted for changes in the level and structure of sectoral activity, fell by a weighted average of 24% between 1973 and 1987. Adjusted primary energy intensities fell by a weighted average of 21%. Since the US energy/GNP ratio fell by 31.8% for delivered

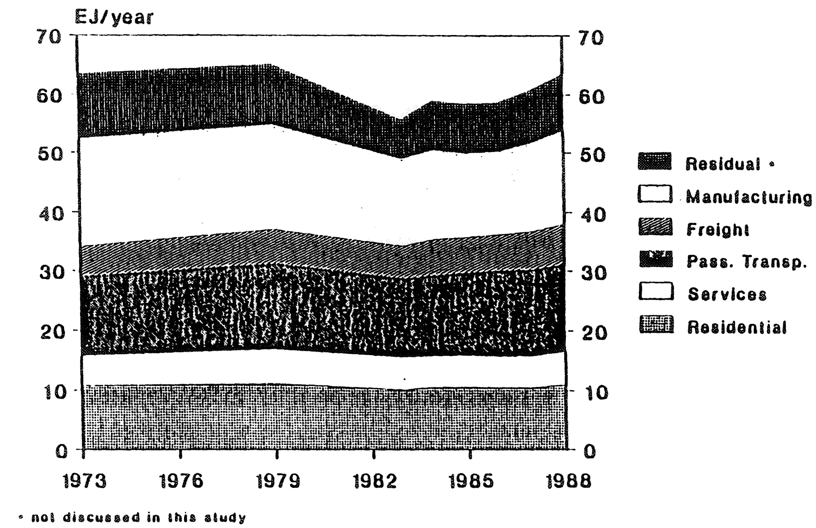

Figure 1 Delivered energy use by end-use sector. The residual category accounts for the difference between total delivered energy and the end-uses covered in this analysis.

energy and 26.3% for primary energy over this period, this analysis suggests that about three-quarters of the decline in the energy/GNP ratio was induced by reduced energy intensity, while the remainder was caused by structural change and interfuel substitution.

2. Actual energy use for the five sectors surveyed in detail was 51.4 EJ in 1987, or 70.7 EJ including electricity generation and transmission losses. Taking into account changes in the level and structure of energy-using activities, the efficiency improvements described above translate into savings of 16.5 EJ of delivered energy or 19.7 EJ of primary energy.

3. The largest reductions in energy intensities occurred for automobile and air travel, home heating, and fuel use in the manufacturing and service sectors. The energy intensity of truck freight, in contrast, actually increased. A decline in load factors and a rise in the importance of light trucks for personal transportation together limited the decline in the system intensity of private vehicles to only 15%.

4. The decline in fuel intensity for most fuel-using processes, together with the increase in the number of electricity-using processes, caused the share of delivered energy as electricity to increase from 11.2% to more than 16%. Direct substitution of electricity for fuel in space and water heating or cooking had only a minor effect on this overall shift.

5. Changes in aggregate sectoral activity levels boosted delivered and primary energy use by 35%. But the activity levels of the freight, passenger

Table 1 Impacts of changing activity levels, sectoral structure, and structure-adjusted energy intensity on sectoral energy use, 1973–1987

Indicator/sector	Definition/description of factors	Impact on sectoral energy use between 1973 and 1987: Delivered energy	Impact on sectoral energy use between 1973 and 1987: Primary energy
Activity			
Passenger transportation	passenger-km/yr	+37%	+37%
Freight	tonne-km/yr	+28%	+28%
Manufacturing	manufacturing value-added	+43%	+43%
Residential	population	+15%	+15%
Services	service sector value-added	+50%	+50%
Weighted average[a,b]		+35%	+35%
Structure			
Passenger transportation	modal mix	+5%	+5%
Freight	modal mix	+4%	+4%
Manufacturing	industry-by-industry value-added shares	−17%	−16%
Residential	household floor area and appliance ownership per capita	+26%	+34%
Services	commercial floor area per unit of value-added, heating fuel switching	−1%	+6%
Weighted average[a]		+1%	+5%
Energy intensity			
Passenger transportation	modal energy intensities[c]	−20%	−20%
Freight	modal energy intensities[c]	−5%	−5%
Manufacturing	industry-by-industry energy intensities	−31%	−26%
Residential	useful space heat energy per unit of home area, electricity per appliance, useful energy per capita for cooking and hot water	−24%	−21%
Services	energy use per unit of commercial floor area	−29%	−18%
Weighted average[a,d]		−24%	−21%
Actual energy use			
Passenger transportation		+13%	+13%
Freight		+27%	+27%
Manufacturing		−21%	−13%
Residential		−3%	+13%
Services		+5%	+25%
Weighted average[a]		−2%	+6%

[a] Weights are shares [illegible] energy use
[b] Real GNP increased by 40% over the period
[c] Includes the impact of changes in load factors
[d] The energy/GNP ratio fell by 32% in terms of delivered energy and 26% in terms of primary energy

transportation, and residential sectors lagged behind the 40% growth in GNP while the proportion of GNP generated in the manufacturing sector remained relatively constant. Only service sector output grew more rapidly than GNP.

6. Structural change reduced manufacturing energy use but increased energy use in the residential, freight, and passenger transportation sectors because the mix of activities became more energy intensive. Overall, structural change within sectors increased US energy delivered use by only 1% and increased primary energy use by 5%.

7. The recent slowdown in the improvement of US energy efficiency has manifested itself in almost every sector, with the possible exception of manufacturing. This slowdown represents a market plateau, not the confrontation with thermodynamic or technological limits. Public policies could restore some of the interest in raising the efficiency of energy use.

TRANSPORTATION SECTOR

Total transportation energy use consists of four components: energy use for passenger transport, freight, natural gas pipelines, and a miscellaneous category that includes off-road equipment, private boats, military activities, and a number of other residual items (6, 7).[2] This section focuses on the first two components, which rose from 17.5 EJ in 1973 to 20.3 EJ in 1987[3] with temporary decreases observed following the oil shocks in 1973 and 1979 caused by declines in transportation activity.

Using data from Oak Ridge National Laboratory (ORNL), we describe the structure of each subsector by noting the contribution of each mode, measured by passenger-km or freight tonne-km, to total subsectoral activity. We obtain fuel use data from the same source. We measure vehicle fuel utilization intensity (VI) in MJ/km for cars and trucks and in MJ/air-km for aircraft. Complementing these fuel utilization indicators are *modal energy intensities* (MI), measured in MJ/passenger-km and MJ/tonne-km for passengers and freight, respectively. Estimates of both VI and MI are available; we use VI to describe technological changes that reduce the fuel use of individual modes and MI to compare modes. Note that the changes in VI and MI are often quite

[2]Our data follow Ross and the Oak Ridge Data Book, with one important [illegible] assumption: We estimate that light trucks provided 7% of passenger travel in private vehicles in 1970, rising to 22% in 1987. We assume that light trucks used as passenger vehicles are driven the same distance but with 10% higher load factors as automobiles. Data from the two Nationwide Personal Transportation Surveys that covered light trucks (1977, 1983) bear out this approximation. Our estimate of light truck fuel economy, however, is taken from values for all light trucks. Note that Ross uses vehicle-km as a measure of activity for autos/light trucks (and for truck freight), and gets somewhat different results because the volume of vehicle-km grew more than that of passenger or tonne-km in these modes.

[3]These figures represent 89% and 90% of sectoral energy use in the respective years.

different because of changes in utilization. These differences can lead to differences in the measurement of energy saved by as much as 25%.

The Structure of Transportation

The total volume of passenger travel increased by 2.2% per year between 1973 and 1987, slightly more rapidly than population, but slower than GNP. During this time the share of air transport increased from 6.5% to nearly 13% of total travel, at the expense of automobiles and light trucks (Figure 2). The share of bus and rail activity, which is low by international standards, fell from 2.4% of travel in 1973 to only 1.9% in 1987. Thus the shift from automobile to air was the major structural change occurring in this sector. If only the mix of modes had changed between 1973 and 1987, travel-related energy use would have increased by 5.3%.

The small share of rail and bus mass transit deserves comment. In some metropolitan areas mass transit carries as much as one-half of all trips to work, but private vehicles dominate all other travel. The long-term decline of the share of transit was reversed momentarily after the oil supply interruptions of 1973 and 1979, but has continued unabated since 1982. The fact that mass transit did not gain market share for any length of time while gasoline prices were high suggests that high energy costs alone were not sufficient to revive mass transit.

Related to the decline in the use of mass transit has been the increase in

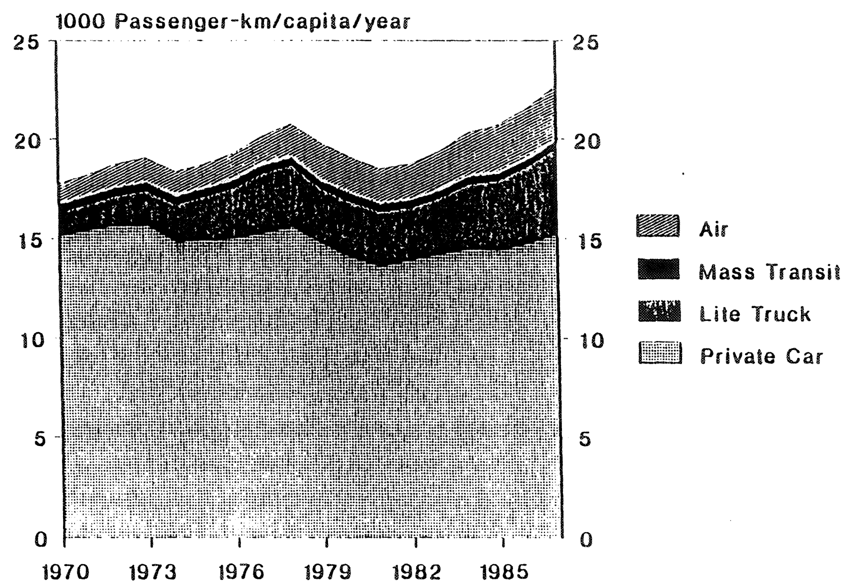

Figure 2 Passenger transporation per capita by mode.

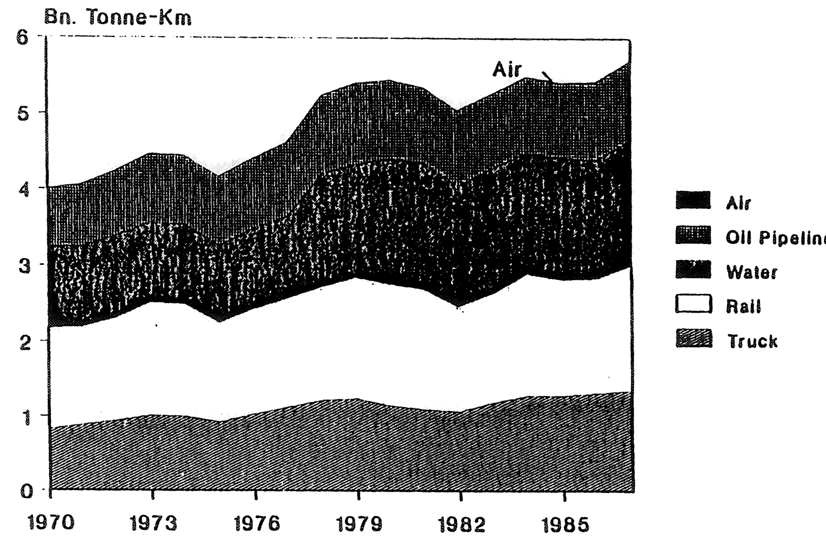

Figure 3 Freight activity by mode.

ownership of personal vehicles. The total number of automobiles and light trucks operated for personal use rose from less than 90 million in 1973 (0.47 per capita) to around 120 million in 1987 (0.60 per capita), or more than one vehicle for every person with a driver's license. But while the number of cars and personal light trucks has grown steadily, the distance travelled per car per year has been remarkably stable, even as fuel prices varied by more than a factor of two (6). This increased vehicle ownership, and therefore greater driving per capita, not increased driving per vehicle, pushed total land travel upwards over time. All the increased ground travel has been carried by these vehicles, resulting in a loss of share for bus and rail modes. Because load factors in cars and light trucks declined from slightly more than 2 in 1973 to around 1.7 in 1987, the growth in passenger-km (1.8%/yr) in this mode did not keep pace with that of vehicle-km, 3.0%/yr.

The total volume of freight (excluding shipments of natural gas[4]) measured in tonne-km, grew at an annual rate of 1.8% from 1973 to 1987. Like travel, freight grew less rapidly than GNP. The level of tonne-km by mode (excluding gas in pipelines) fluctuated over time (Figure 3). The share of trucks increased slightly, and within trucking, the share of lighter, short haul trucks

[4]Approximately 20% of freight energy use was in the form of natural gas used to run compressors for natural gas pipelines. Unfortunately, no measure of tonne-km for gas shipments is available. Since natural gas substitutes for coal and oil, both of which are counted in freight shipments, the omission of natural gas is unfortunate. Similarly the small weight of water and coal-slurry shipped is also unavailable.

increased as well. If only the mix of modes had changes between 1973 and 1987, freight-related energy demand (excluding natural gas) would have increased by 3.6%.

Although the modal mixes for both passenger and freight transportation shifted towards modes with higher modal energy intensity, the volume of activity for each grew less rapidly than GNP. On balance, these changes reduced transportation energy use relative to GNP.

Intensity and Efficiency

Key energy-using vehicles became less energy-intensive during the 1970s and 1980s. The VI of automobiles fell by 33% to 4.3 MJ/vehicle-km or 19.1 MPG between 1973 and 1987. Light truck VI, which is higher than that of automobiles, fell less, by 19% to 5.9 MJ/vehicle-km. But the share of light trucks used as passenger vehicles increased to over 20% of the private passenger vehicle stock. When figures for these two vehicle types are combined, the result is only a 28% decline in the VI of private vehicles. The VI for air travel decreased by 22.7% between 1973 and 1987, to 305 MJ/km (7). Additionally, energy use per seat-km fell by more than 40% because the number of seats per aircraft increased from 111 in 1970 to 161 in 1987. Technologically, then, VI fell significantly for major modes.

Utilization patterns had different impacts on these modes. Load factors for automobiles and light trucks fell from approximately 2.0 occupants per vehicle in 1973 to 1.7 in 1987 (8).[5] As a result, the MI of private vehicle travel increased through 1979, and only fell 15% overall between 1973 and 1987. Load factors for transit buses fell, increasing energy intensity, but load factors for AMTRAK increased, causing the energy intensity of intercity rail travel to fall. Load factors for air travel increased significantly, from 54% of available seats filled in 1973 to 62% in 1987. This change, combined with the introduction of more efficient aircraft, caused the MI of air travel to fall by almost 50% between 1973 and 1987. Overall, the MI of passenger travel declined by 18% from 3.27 MJ/pass-km in 1973 to 2.69 MJ/pass-km in 1987. The decline in individual intensities alone caused a 20% decline in this intensity.

The fuel economy of automobiles improved significantly. As a review by Ross (6) shows, most of this improvement came about through improvements in the economy and performance of new cars of a given interior volume; "downsizing" of the fleet had only a minor impact on fuel economy. Furthermore, Ross shows that engine power per engine size increased. In other words, the performance of new cars sold in the United States improved, but

[5]Automobile load factors are estimated by ORNL from the Nationwide Personal Transportation Surveys (1969, 1977, 1983). Light trucks were included in 1977 and 1983. We have assumed that load factors and driving distances are approximately the same for both vehicle types.

VI fell. US Environmental Protection Agency (EPA) tests indicate that the sales-weighted fuel economy of new automobiles increased to 28.5 miles per gallon (mpg) (8.3 liters per 100 km) in 1988. The combined new car/light truck average moved from 15.3 mpg in 1975 to 25.8 mpg (9.2 liters per 100 km) in 1988.

Two factors prevented these dramatic improvements from fully affecting actual on-road fuel economy. Ross gives the test mpg of light trucks as 21 in 1988, down slightly from 1987, while that of automobiles rose to more than 28. The increased importance of light trucks with lower fuel economy than that of automobiles has thus restrained the improvement in overall new personal vehicle fuel economy. Second, the actual EPA tests do not represent real fuel economy, something well known for many years. This is because driving in the city is not well simulated in the EPA tests. Moreover, the distortion may have increased over recent years (9). The share of driving in cities has increased (DOE calls this the "rural-urban shift"), and the congestion in cities, which depresses fuel economy, has worsened. Thus test mpg may diverge as much as 22% from real mpg today as compared to the 15% bias of the 1970s. This distortion applies to light trucks as well as cars.

The dramatic improvement in air fuel economy was documented by Gately (10). New aircraft require significantly less energy per seat-mile than do older ones, both because of improved engines and aerodynamic characteristics (i.e. technology) and because most newer aircraft of a given type have more seats (i.e. structure). For example, a Boeing 767 yields more than 60 seat-miles per gallon, while a 707 of the original, pre-1960 vintage, gives less than 40. The number of seats on many older aircraft has been increased. In some cases, the engines on existing planes were upgraded, often in response to noise reduction regulations. As a result of these changes, seat-miles per gallon increased for almost every type of aircraft, typically from 30 to 40 for narrow-bodied planes (707s, 727s, and 737s) and from 40 to almost 60 for the wide-bodied models (747s, DC10s, and L1011s).

Changes in operations practices had an impact on fuel economy, too. As noted above, the average load factor increased (7). Stage length, or the distance flown per flight, increased by 23% from 742 km in 1978 to 917 km in 1988 (11). This change increased fuel economy, because planes spend a greater part of their flight actually cruising as stage length increases. Average speed should then increase, for the same reason. Yet average speed, as estimated by the US Federal Aviation Administration (FAA), was about the same in 1978 as in 1988. That average speed did not increase suggests that congestion around airports slows aircraft, increasing fuel consumption per trip as planes circle or take other measures near cities. It appears therefore that these two operational factors offset each other.

The story for freight was different than that for passenger travel. Ship and rail freight intensities each declined by about 30%. But truck freight intensities increased slightly by 6%, from 2.96 MJ/tonne-km in 1973 to 3.14 MJ/tonne-km in 1987.[6] Altered utilization patterns appear to be the reason for the increase in intensity, as well as a gradual increase in the importance of light trucks with low loads. Overall, the change in intensity of all modes alone through 1987 would have decreased freight energy use by 4.5%, but structural changes towards greater truck freight offset this decrease by 3.6%.

According to statistics cited by ORNL (7), the VI of light trucks, measured in MJ/km, fell by 19% between 1973 and 1987. The VI of other single unit trucks fell by 5% between 1973 and 1982 but has since increased over time. And the VI of combination trailer/trucks fell by about 5% over the entire period. When the entire stock is weighted using the Truck Inventory and Use Surveys of 1977 and 1982 (12), VI drops approximately 10%. Because these changes are so small, changes in the utilization and mix of trucks affected freight MI more than changes in the fuel economy of individual classes of trucks. The small improvement in fuel economy was more than offset by the other changes in utilization patterns that increased the energy intensity of freight haulage. In spite of the uncertainties, this finding suggests research is needed to improve the overall energy performance of trucking.

Conclusions: Energy Efficiency in Transportation

Between 1973 and 1987, the components of transportation energy demand changed significantly, as Figures 4 and 5 show. Overall, transportation energy use declined relative to GNP. The most important single component in this decline was the reduction in the energy intensity of passenger travel. The vehicle efficiency of the three major transportation modes has improved since 1973. Fleets of personal vehicles, aircraft, and trucks were 28, 40, and 10% less energy intensive in 1987 than they were in 1973. This change alone saved more than 7 EJ/yr of energy by 1987. Lower load factors in personal vehicles increased energy use by 1.4 EJ, and lower load factors and shifts to more local freight traffic increased energy use for freight by more than 0.6 EJ. Although our figures are not strictly combinable in a linear way, the savings implied by these three changes are consistent with the 4 EJ that PNL and DOE estimated were saved between 1972 and 1986.

In 1989 the VI of new personal vehicles and aircraft was approximately

[6]Unfortunately there are no complete data for US freight haulage, only estimates of intercity tonne-km and energy use. Freight carried by light trucks was estimated by assuming they carry 100 kg for the vehicle miles not assigned to personal light trucks. Intracity freight carried by heavy trucks was estimated from the difference between vehicle-miles of heavy trucks in intercity travel and in all travel, multiplied by 2.5 mt to represent a load. Over a wide range of assumptions for these values there seems no question that the total energy used by trucks increased faster than the total volume of freight.

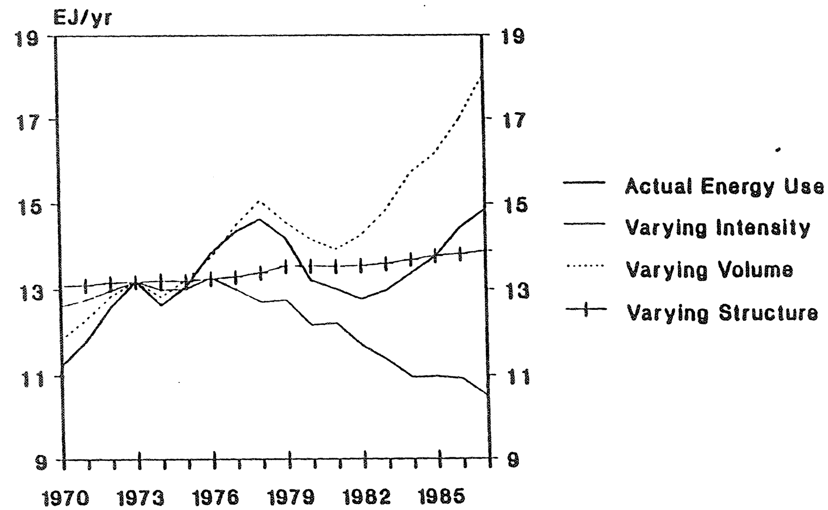

Figure 4 Passenger transportation delivered energy use. Evolution of actual and hypothetical transportation energy use for travel. Each "effect" is computed by having only modal intensity, activity, or structure (modal mix) follow its actual path while holding the other two components constant at 1973 levels.

25% less than that of the existing vehicle stock, ensuring technological decreases in fuel needs that are irreversible for the next several years. But whereas the load factors of aircraft increased in the 1970s and early 1980s, lowering MI even more, utilization of both automobiles and trucks worsened, in the latter case enough to cause an increase in MI. And preliminary data suggest that the automobiles and light trucks purchased in 1989 will be more fuel intensive than those purchased in 1988. The VI of other trucks stopped declining in 1982. Moreover, preliminary operating data from 1988 suggest that fuel use per passenger-km for commercial aviation in 1988 was no lower than in 1987. And average speed was headed downward, suggesting more congestion at airports. Thus the rate of improvement in actual fuel economy in major transportation modes is clearly slowing down. While all three modes show promise for further improvements in technological efficiency, these improvements have been slowed by lower fuel prices and other factors.

OUTLOOK

Automobile transport is the single most important energy-using activity in the US economy. Thus changes in the fuel economy of cars will be important to

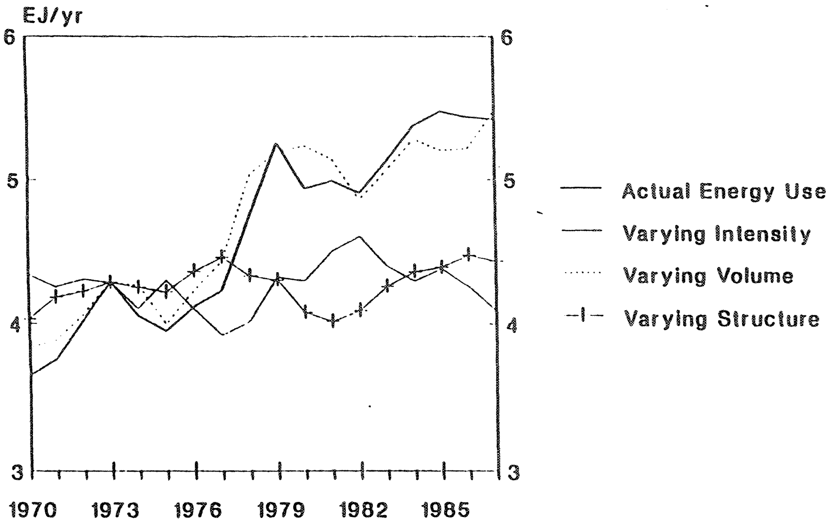

Figure 5 Freight transportation delivered energy use. Evolution of actual and hypothetical energy use for freight transportation. Each "effect" is computed by having only intensity, activity, or structure (modal mix) follow its actual path while holding the other two components constant at 1973 levels.

the nation's energy future. Not surprisingly, there is concern over the recent flattening of the fuel intensity of personal vehicles. Figure 6 shows key features of this plateau. Indexed to real (or estimated) 1973 values are actual fleet and test new vehicle fuel intensity (including that of light trucks) as calculated by Ross (6), the real gasoline price, the real cost/km of using gasoline, i.e. the price index times the fuel utilization index. The sudden decline in price (and cost) in 1986 is clear, as is the slow drop of equal magnitude between 1982 and 1986. Not surprisingly, the decline in fuel intensity slowed after 1982 and may have reversed in 1989. Indeed, the fuel economy of cars imported into the United States peaked in 1983. Have auto manufacturers exhausted ways of improving fuel economy?

The literature is replete with reviews of the potential for further improvements in fuel economy (6, 13–17). These references all point to a large number of prototype cars that use less than 50% as much fuel per seat-km as today's average new car, and hence less than 33% of the present fuel per km. In conversations with major automobile producers worldwide (including BMW, Volkswagen, Volvo, Peugeot, and General Motors), however, we found that the outlook for stable oil prices has all but erased fuel economy as a major concern for auto manufacturers. Similarly, the lull in gasoline prices has permitted, if not encouraged, Americans, Japanese, and Europeans to

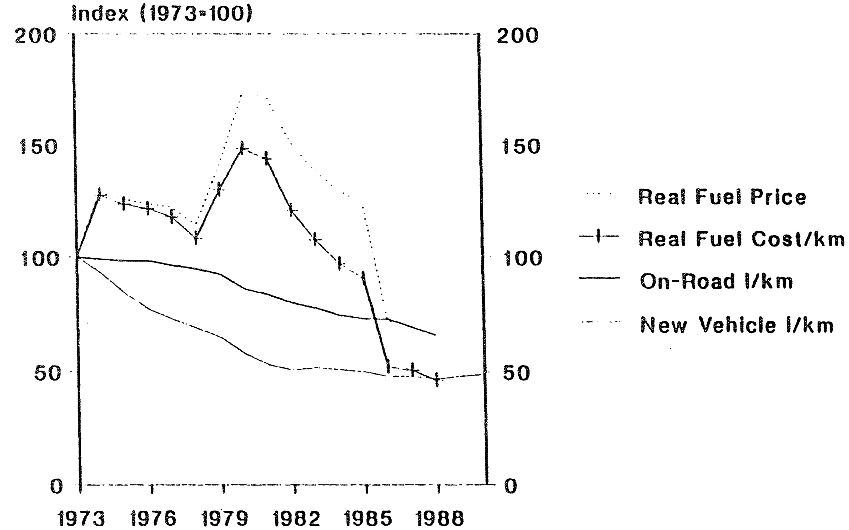

Figure 6 Personal vehicle fuel economy. Evolution of new-car and on-road fleet mpg and prices in the United States. Prices are taken from *Monthly Energy Review*. The on-road vehicle fuel economy figures are calculated in this study by summing values for cars and personal light trucks. The new vehicle figures include all light trucks sold. Sources: ORNL, ACEEE, LBL-IES

manufacture and buy more powerful and often larger cars in recent years. Thus the plateau (and apparent reversal) in the weighted improvement in fuel economy are as much a result of consumer indifference as of manufacturer disinterest. As Ross (6) shows, total driving costs are relatively insensitive to fuel costs. This was particularly true in 1988, when the real gasoline cost of driving one km in the United States and many European countries was the lowest in decades.

Difiglio et al (17) catalogue technologies that would improve test new-car fuel economy to nearly 40 mpg with no loss in amenity. Using a 7% real discount rate and amortizing the increased costs over 10 years, Carlsmith et al (18) found that improvements to 38.5 mpg would be cost effective at a gasoline price of $1.43/gallon in 2000. But these discount rates are not typical for consumers' purchases of energy-using goods, as Rudermann et al showed for appliances (19). Greene (20) finds that both the Corporate Average Fuel Economy (CAFE) standards and to some extent higher fuel prices caused the decline in fuel intensity after 1975, stimulating both consumers and producers to focus on fuel economy. But with standards frozen today, there is no pressure from this powerful stimulus. Moreover, with fuel prices and costs as low as they were in 1989, it would be difficult to believe that fuel intensity would continue to decline rapidly, although technological improvements could certainly keep pace with increases in interior room and power. The high-mpg prototypes may never be commercialized, although important components tested in these models may appear soon in ordinary automobiles. Standards of some kind, combined with higher fuel prices, possibly through taxes, appear necessary components of any policy designed to get both producers and buyers to focus on fuel economy in the near future.

The fuel economy of trucks should not be overlooked. Better engines, better aerodynamic designs, and, in some states, permission to pull two trailers, all could contribute to lower VI. But the truck freight system itself has evolved towards a more energy-intensive mix of short haul modes and smaller trucks, as a result of shifts in the kinds of products being shipped and the patterns of shipping. And traffic congestion increases truck fuel use. While the intensities of other freight modes have declined since 1973, these modes have played a declining role vis-a-vis trucks, whose fuel use dominates the subsector. As a result, the probability that the energy intensity of freight hauling will fall over the short term future is slim.

The third most important subsector of transportation is air travel. According to experts at Boeing (D. Wallace, private communication), three important factors will affect future passenger aircraft fuel economy. Gradual improvements in control technologies will reduce energy requirements somewhat; breakthroughs in materials technologies that permit engines to operate at higher temperatures could boost engine performance significantly; better scheduling and controlling will reduce losses at and around airports. Each of these changes could reduce fuel intensity by 5–10%. More dramatically, adoption of the by-pass fan engine would reduce fuel intensity by 30% or more. But both Boeing and McDonnell-Douglas have put off development of this engine indefinitely. The cost of new developments, expressed as an incremental capital cost for new aircraft, is too high relative to the cost of fuel. Hence expectations are for only gradual improvements through better flying controls.

Just as for automobiles, aircraft energy intensity also depends on system performance. Passengers per flight increased all through the 1970s and 1980s, but recently airlines have found it profitable to insert business class seats in place of economy, reducing the total seating/aircraft available. Congestion at and around airports is another factor affecting energy intensity. And stage length also has a fundamental impact on fuel use. Nevertheless, virtually every new airplane entering the US (and world) fleet is more efficient than the present fleet itself. This efficiency gain is greater than the potential offsetting effects of slight declines in seating capacity or load factor. Thus the principal uncertainty over future aircraft fuel performance is that of the rate of decline of fuel intensity.

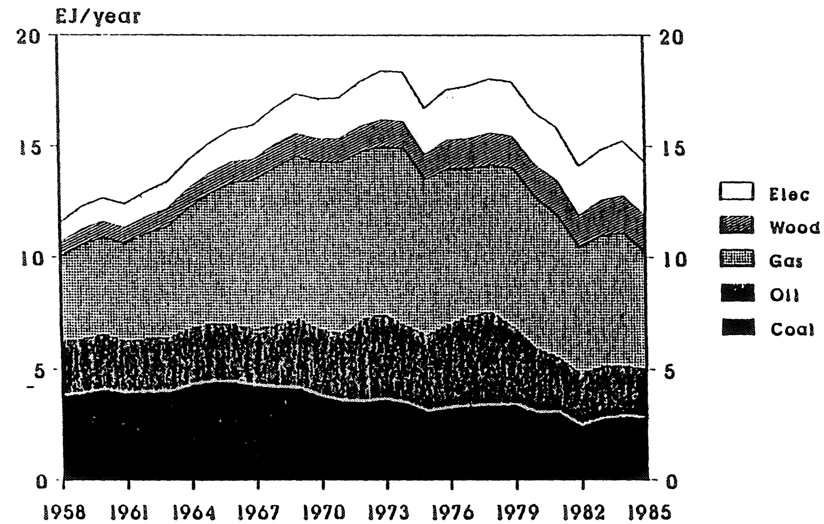

Figure 7 Manufacturing energy use by fuel type.

MANUFACTURING SECTOR

The US manufacturing sector, which consists of a range of industry groups involved in the transformation of raw materials and intermediate goods into finished products, used 14.3 EJ of energy for the provision of heat and power in 1985 (Figure 7). While an additional 4.1 EJ of energy products were used by the sector as feedstocks in the production of asphalt, organic chemicals, and other goods, these products were excluded from our analysis on the grounds that they should properly be counted as material rather than energy inputs.

We gathered data on the energy use and economic activity of six energy-intensive manufacturing industry groups—paper and pulp (SIC[7] 26); industrial chemicals (SIC 28 excluding 283–285); stone, clay, and glass (SIC 32); iron and steel (SICs 331, 332, and 339); nonferrous metals (SICs 333–336); petroleum refining (SIC 291)—and a residual category ("other") that encompasses the range of non-energy-intensive manufacturing activities.

Unfortunately, the available statistics on manufacturing energy use are less than adequate in a number of respects. Although the Census Bureau (21, 22) published data on manufacturing energy use for the years 1954, 1958, 1962, 1967, 1971, and 1974–1981, this series was discontinued in more recent years as the federal government cut back its efforts to gather and publish energy data. Moreover, the Census data account only for inputs of purchased fuels

[7] "SIC" is an acronym for the US Standard Industrial Classification system.

and electricity, and exclude self-produced fuels such as the still gas used in petroleum refining and the wood waste used in the paper and pulp sector that together account for some 29% of sectoral energy use. More recently, the Energy Information Administration (EIA) carried out a survey on manufacturing energy use (23) that both provided data for the 1985 calendar year and measured the use of nonpurchased fuels. But while EIA plans to repeat this survey at three-year intervals, no comprehensive data on manufacturing energy use are available past 1985.

The manufacturing energy data used in this report were taken from the US National Energy Accounts (NEA) (24), which use a variety of government and nongovernment statistics—including the Census and EIA data—to provide a consistent series of annual energy use data for the years 1958 to 1985. These data account for the total use of fuels and electricity for heat and power and distinguish between oil, natural gas, coal, wood, and electricity consumption.

The measurement of manufacturing activity involves both conceptual and practical difficulties. While the real value-added statistics published by the Commerce Department (25) are often used in the analysis of trends in industrial production, these data are estimated as the algebraic difference between dollar values of outputs and intermediate inputs in each year, evaluated at base-year prices. Consequently, trends in Commerce Department real value-added depend not only on output trends per se but also on changes in the efficiency with which inputs are used to produce output. Value-added will increase, for example, if production remains constant but technological improvement leads to reduced input requirements per unit of output.

To circumvent this difficulty, the Industrial Production Indices published by the Federal Reserve Board (FRB) (26, 27) were used to measure manufacturing activity for the purposes of this study. These statistics measure the physical production of each product class weighted by its contribution to sectoral value added in the base year (1977). The result is a series of real value-added data that in principle account strictly for changes in physical production.[8]

The energy intensity of each industry group is thus defined as energy use per unit of FRB industrial production, measured in energy per unit of value-added. Our analysis investigates the impacts of changes in the level of sectoral output, changes in the structure or composition of this output between industry groups, and changes in industry-by-industry energy intensity on the evolution of manufacturing energy use.

[8]Unfortunately, physical production is not readily defined in certain industry groups. As a result, the FRB makes limited use of data on inputs—including, in some cases, electricity consumption—as surrogates for output. While this practice obviously compromises the quality of the data to some extent, the application of this technique is limited to a small number of industry groups.

The Structure of the Manufacturing Sector

The manufacturing sector consists of a large number of diverse industry groups that employ an even broader range of process technologies to transform raw materials into finished goods and services. This inherent complexity imposes certain limitations on energy analyses that do not generally hold for other end-use sectors. In the residential and transport sectors, for example, it is possible to relate energy use to specific technologies and to measure efficiency changes explicitly over time. In the manufacturing sector, on the other hand, one must either carry out detailed technological analyses of particular processes or facilities or else focus on the analysis of relatively aggregated data.

The analysis is greatly simplified, however, by the fact that manufacturing energy use is largely dominated by sectors involved in the processing of raw materials. The energy-intensive industry groups described above, although they account for only 18% of manufacturing value-added (Figure 8), are responsible for 56% of sectoral electricity use and 74% of total energy use (Figure 9). Accordingly, shifts in the product mix between the various energy-intensive industries or between raw materials and light manufacturing may have significant impacts on sectoral energy use.

To gauge the impacts of structural change on manufacturing energy use we calculated the evolution in energy use broken down by fuel type that would have occurred if the total output level and the energy intensities of each

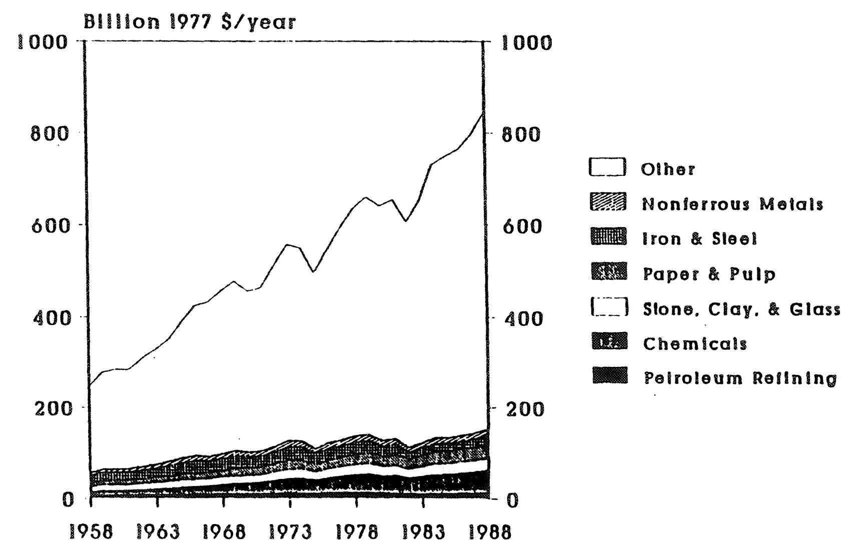

Figure 8 Manufacturing activity. Value-added by subsector.

fluctuations. Manufacturing output, as it is conventionally measured, has grown with the economy for the past two decades, and there is no particular reason to believe that this relationship will decouple over the short to intermediate term.

Intensity and Efficiency

Changes in energy intensity, or energy per unit of value added in a particular industry, will reflect changing efficiency perfectly only if there is no change in the mix of products produced within that industry. Our preliminary analysis of the ratio of the physical production of energy-intensive raw materials to real value-added in the industry groups in which those materials are produced has shown that structural changes may have been important in sectors such as chemicals, where the production of plastics increased substantially relative to other commodities; and in stone, clay, and glass, where the production of cement fell by 20% relative to value added. But the literature to date has shown that the most important impacts of structural change may be captured at a relatively high level of aggregation such as the one used in this analysis (30, 31). Thus while the figures discussed in this section should be regarded properly as indicators rather than measures of energy efficiency, we believe that energy-intensity trends as measured in this analysis are driven mainly by efficiency improvements.

To measure the impacts of changing energy intensities on manufacturing energy use, we estimated the evolution in energy use that would have occurred between 1958 and 1985 if the output of each industry group had remained constant at its 1973 value while its energy intensity followed its historical path. According to this calculation, structure-adjusted manufacturing energy intensity declined by 2.5% per year between 1958 and 1973 (Figure 11). While this decline was led by a 58% decline in coal intensity, the intensity of oil, gas, and wood use declined by 23%, 15%, and 17% respectively. Electricity intensity, on the other hand, remained relatively constant over the period.

The 1973 to 1985 trend in energy intensity is remarkably similar. On aggregate, structure-adjusted energy intensity fell by 2.7% per year between 1973 and 1985—only slightly more rapidly than the 1958–1973 trend. On a fuel-by-fuel basis, the intensity reductions were 44%, 37%, and 15% for oil, gas, and coal, respectively. Wood intensity increased by 6%, while electricity intensity dropped by some 6%.

Together, these statistics point to considerable improvements in manufacturing energy efficiency over time. But these changes were arguably driven as much by long-term changes in process technologies as by short-term responses to changes in the relative price of energy. It is indeed striking and even counterintuitive that the energy shocks of the 1970s did not induce a significant increase in the rate with which manufacturing energy intensity

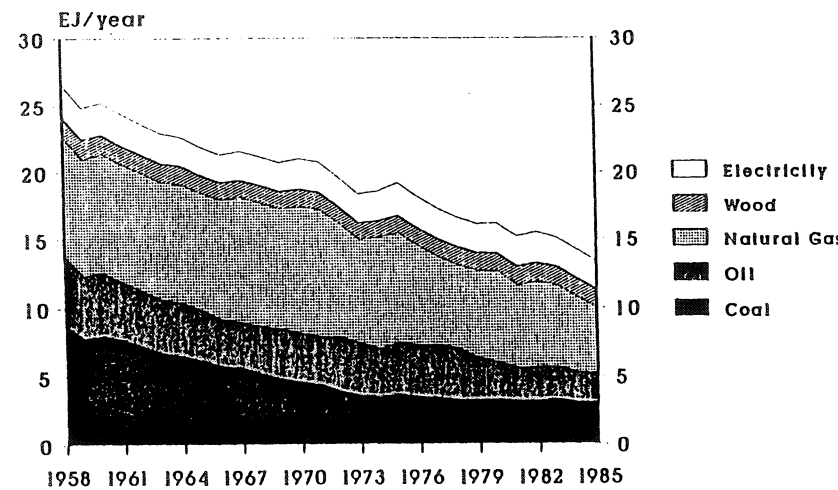

Figure 11 Manufacturing energy use. Impacts of intensity changes. This shows the hypothetical evolution of energy use in manufacturing if activity and value-added shares of the subsectors (structure) had remained constant at 1973 levels and only intensities had followed their actual paths.

fell. Should not higher energy prices have pushed producers to develop and implement energy-saving technologies that were not cost-effective at the low energy prices of the 1960s?

The following line of reasoning may explain this observed disparity between expectation and realization. Energy accounts for only a small fraction of total input costs in all but the most energy-intensive industries, so research and development programs generally focus more on capital and labor productivity and product quality than on energy saving. But technologies that produce capital and labor savings generally save energy as well, so that the energy efficiency of new manufacturing technologies improves over time, even at low energy prices. The energy price increases of the 1970s presumably led producers to invest in focused energy-saving technologies. But the annual rate of manufacturing output growth slowed from 5.4% between 1958 and 1973 to 2.5% between 1973 and 1985. Hence while new technologies may have been designed with more attention to energy costs, investments in new technology slowed along with output growth. On balance, then, the rate of energy-efficiency improvement remained more or less constant.

Manufacturing Energy Intensity, 1985–1987

As noted above, the most recent year for which comprehensive data on manufacturing energy use are available is 1985. It is therefore not feasible to extend the analysis presented in the preceding section to more recent years. Data are available, however, on the use of fuel and electricity for heat and power in the aggregate industrial sector, which includes manufacturing, mining, agriculture, and construction. These data were prepared by subtracting the use of energy feedstocks from the industrial energy statistics published by the Energy Information Administration (32). If we assume that the rate of energy-intensity change was the same in manufacturing and nonmanufacturing industries, and that structural shifts between manufacturing and other industries were small, then changes in the ratio of industrial energy use to total industrial production give an approximate measure of recent trends in manufacturing energy intensity. When this calculation is carried out, we find that aggregate energy intensity fell by 4.1% between 1985 and 1987; fuel intensity fell by 4.6%; and electricity fell by 1.9%. These savings were focused mainly on the 1985–1986 interval. Little change in energy intensity occurred between 1986 and 1987; electricity intensity actually increased by 1.2%. (See NOTE ADDED IN PROOF on p. 501.)

While this approach lacks analytical rigor, it is defensible on the basis that the manufacturing sector accounts for some two-thirds of industrial production and four-fifths of industrial energy use. As we noted above, structural change had no significant impacts on manufacturing energy use between 1985 and 1987. Moreover, the composition of total industrial production between the various component sectors did not change substantially over the period. In any event, such casual analysis will have to suffice in the absence of more authoritative data.

We note, however, that recent trends in selected industry groups support the hypothesis that energy intensities are continuing to fall even in the post-1985 era of low energy prices. Unpublished data from the Iron and Steel Association (E. Young, private communication), for example, indicate that the energy intensity of that sector fell by 11.5% between 1985 and 1988, or 4.1% per year. This improvement was spread across the range of technologies used in the industry. Similarly, statistics from the American Paper Institute (J. Metz, private communication) indicate that an energy intensity reduction of 2.1% occurred in the paper industry between 1987 and 1988. This number grows to 7.5% when adjustments are made to account for changes in capacity utilization, the fuel mix, and other "structural" factors. Since the annual reductions averaged 3.2% between 1972 and 1988—or 3.5% on an adjusted basis—it is clear that recent improvements are consistent with long-term trends. Energy intensity also fell in the chemicals sector between 1985 and 1988 according to unpublished data from the Chemicals Manufacturing Association (J. Parker, private communication). While the use of fuels and electricity consumed for heat and power increased by 14% over the period, sectoral output increased by 20%. Thus energy intensity fell by a total of 5.0%, or 1.7% per year.

Fuel Mix

The use of oil and natural gas fell rapidly as the prices of these fuels rose in the 1970s. It is often suggested that one of the factors behind this trend was the substitution of solids and electricity for oil and gas. Indeed, the manufacturing fuel share of wood rose from 7% to 12% between 1973 and 1985, while the electricity share rose from 12% to 17%. The coal share, in contrast, remained constant. But the utilization intensities of these fuels did not rise substantially over the period—indeed, electricity intensity, adjusted to account for the impacts of structural change, decreased by 6%. Thus while interfuel substitution was undoubtedly important in some applications, on the whole oil and gas savings were apparently generated more by conservation than by substitution.

Conclusions: Energy Efficiency in Manufacturing

We have documented that enhanced energy efficiency has been an important factor shaping the development of manufacturing energy use. But just how much energy was saved by the energy intensity reductions that occurred between 1973 and 1987? The fact that statistics are not available on actual manufacturing energy use in 1987 complicates the analysis. But if we assume in light of the information presented above that aggregate manufacturing fuel intensity fell by 4.6% between 1985 and 1987 while electricity intensity fell by 1.9%, and multiply these intensity estimates by actual 1987 manufacturing activity, we find that the manufacturing sector used approximately 12.1 EJ of fuel and 2.5 EJ of electricity in 1987. If, however, the energy intensities of each industry group had remained fixed at their 1973 values, manufacturing fuel and electricity use would have been 19.0 EJ and 2.8 EJ respectively given the actual level and structure of output in 1987. Thus energy intensity reductions between 1973 and 1987 saved about 6.9 EJ of fuel and 0.3 EJ of electricity for an overall improvement of 33%.

Outlook

Future energy use trends in the manufacturing sector, as in the other sectors considered in this analysis, are difficult to divine. In the absence of compelling evidence to the contrary, we expect that manufacturing output will continue to grow more or less with GNP. A number of analysts have suggested that the structure of manufacturing production will continue to evolve away from energy-intensive raw materials industries (28). But the structure of manufacturing has apparently stabilized in recent years, halting the downward pressure on energy use that persisted throughout the late 1970s and early 1980s. Future structural trends are therefore highly uncertain and deserve further research.

The future of manufacturing energy efficiency, on the other hand, is more easily forecast. As we noted above, sectoral energy intensity declined at an average annual rate of 2.6% per year between 1958 and 1985 with no significant departures from the trend over the entire period. Moreover, a range of studies have suggested that a continuing improvement of 1–2% per year will be realized under expected economic conditions through the turn of the century (28, 33, 34).

Of particular interest is a series of engineering studies of the potential for efficiency improvements in five industries—steel, cement, paper and pulp, glass, and textile manufacturing (35–39). The studies indicate that the chances are "very good" that the aggregate energy use per unit of physical production of the sectors in question could be reduced by roughly 30% (1.4% per year) between 1985 and 2010 using current "state of the art" technology. Reductions of approximately 40% (2.8% per year) are "possible" based on the use of advanced technology.

The extent to which new energy-efficient technologies penetrate the manufacturing sector will be generated in part by the rate of output growth (which determines investment in new facilities) as well as by energy prices. But we expect that manufacturing energy intensity will continue to decline at a healthy rate, although perhaps not as rapidly as in the past, as cost-conscious managers seek to cut production costs.

RESIDENTIAL SECTOR

Total final US residential energy use remained relatively constant in the 1970s and 1980s, fluctuating between a high value of 10.9 EJ in 1979 and a low of 10.0 EJ in 1982 (Figure 12), but rising to nearly 11 EJ by 1988. Primary energy use, however, rose over most of the period with plateaus in the years following each energy shock (40).[9]

During this time period, important changes took place in the characteristics of the sector and the fuel mix. Population, which we take as our measure of residential activity, and the number of dwellings increased substantially, and the fuel mix changed as well. We must further disaggregate energy use by fuel and end use in order to separate the effects of these changes from the impact of greater efficiency. To do this, we compare energy use for appliances, hot

[9]These data are based on the State Energy Data System (SEDS) reports, but include wood as estimated by the Energy Information Administration and the use of gas and oil in apartment buildings, uses of energy omitted from SEDS. Weather adjustment is carried out by dividing the apparent consumption of electricity and fuels for space heating by the ratio of actual to long-term average degree-days. When individual fuels are compared over time, the degree-day series account for the distribution of homes heated by each fuel.

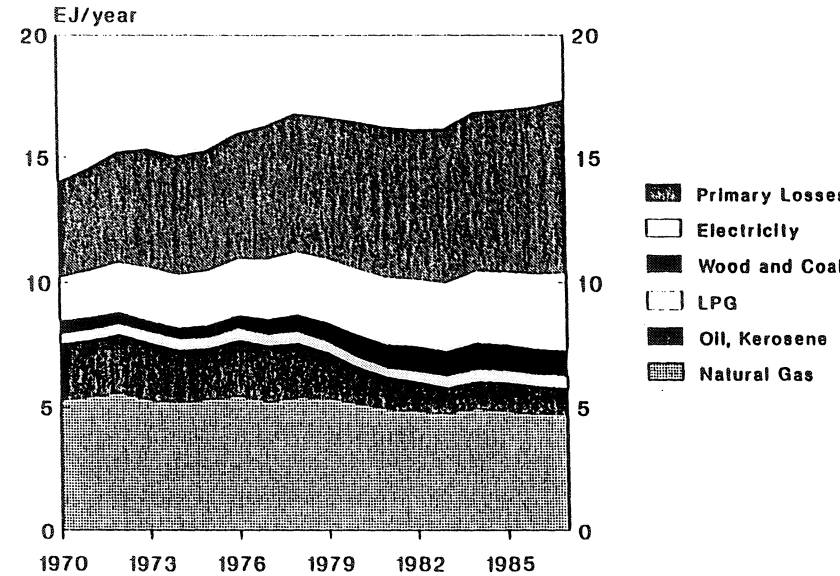

Figure 12 Residential energy use. Energy use by fuel.

water, and cooking (41) with household population, and we compare space heating with the number of homes or, where data are available, with square meters of heated floor area. These comparisons yield energy intensities that we use to estimate the impact of improved energy efficiency. We then reaggregate the components of energy use in a way that allows us to separate the effects of changes in energy intensities from other factors that may have affected energy use significantly.

Meyers (40) presented a comprehensive summary of time series data showing energy use by fuel (including wood); fuel choices for space heating, water heating, and cooking; housing and household characteristics; weather; and other features of the residential sector. Using these data and our estimates of how much of each fuel is used for each purpose, we obtain the estimates of useful residential energy use per dwelling shown in Figure 13. By our measure of useful energy, delivered quantities of oil and gas are counted at 66% efficiency, solids at 55%, and electricity at 100% to account for differences in the utilization efficiencies of the various fuels at the point of end use. We have adjusted yearly data for variations in temperature (41). By 1987, delivered energy use per dwelling had fallen by 24% relative to 1973, useful energy per dwelling had fallen 22%, and primary energy use per household or occupied dwelling was 14% below its 1973 value. These declines suggest significant conservation of fuels and electricity.

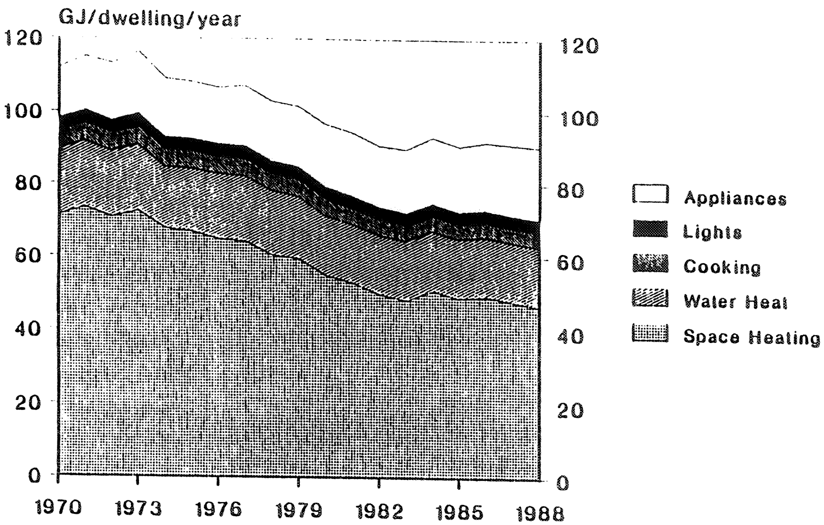

Figure 13 Residential energy use. Useful energy per household by end use, adjusted to normal weather. Useful energy is calculated by counting liquid and gaseous fuels at 66% efficiency and solids at 55% to account for conversion efficiencies of different fuels.

The Structure of the Residential Sector

Between 1973 and 1987, important changes in the characteristics of US homes occurred. While the penetration of central heating (here defined as the presence of a furnace or boiler circulating hot air or water through the home, a central heat pump, electric furnace, or built-in baseboard electric heating) increased slowly over the period to around 80%, the average heated floor area increased from 130 m^2 to nearly 140 m^2, which boosted space heating and lighting requirements in an approximately proportional fashion. Cooking and water heating equipment was virtually saturated in 1973. The ownership of major appliances (refrigerators, freezers, washers, dryers, air conditioners, and dishwashers), in number of units weighted by 1973 unit energy utilization of each unit, increased by 28% over the period.

Other important changes took place in the characteristics of households and homes. First, household size declined from 3.06 persons per household in 1973 to 2.72 in 1987. Schipper et al (42) suggested that energy use per household at a given time varies approximately with the square root of household size. For the parameters presented above, energy use per household should have declined by about 6%. But the decline in household size can be viewed as an increase in the number of households per capita of 13%. Thus the decline in household size leads to an overall increase in energy use per capita of approximately 6.5%. Second, the regional distribution of homes

shifted slightly, such that the average number of heating degree-days declined by nearly 3% between 1970 and 1980 (40). This decreased space heating requirements but increased cooling needs. On balance the geographical shift should have decreased delivered energy use by about 2%, a small effect.

Household activity, as measured by population, increased energy use by 15%. The structural factors outlined above together increased final energy use by 20%, primary energy by 26%. The total increase in primary energy use driven by changes in the level and structure of residential activity should have been 45%, slightly greater than that of the GNP. As it turns out, household energy use was restrained considerably by improved efficiency, as we show below.

Fuel Mix

During the 1970s and 1980s, major changes occurred in the mix of fuels used in US homes, as Figure 12 implies. Changes occurred for two reasons. First, existing homes switched from oil to gas and wood in space heating, from oil to electricity in water heating, and from gas to electricity for cooking. The switch in space heating was particularly rapid between 1978 and 1985, when more than 5 million homes switched away from oil heating (Figure 14) (43). Second, builders chose a significantly different mix of fuels for new homes than that of the existing stock. Gas and electricity are used in preference to oil

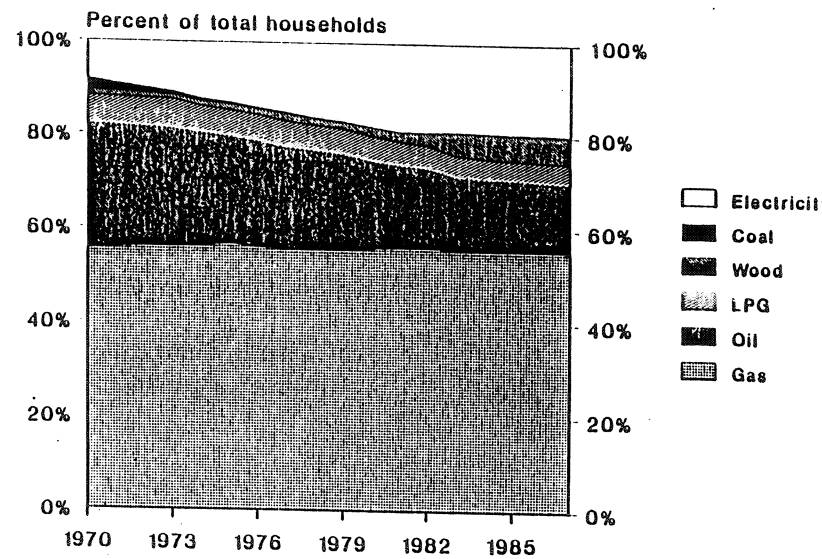

Figure 14 Principal household heating fuels. Share of homes using the indicated fuel as the principal space heating fuel. Sources: Meyers, RECS, US Census Bureau

in new-home space heating, and the share of electricity for space and water heating is much higher in new construction—around 50%—than in existing homes. By the second half of the 1980s, the shares of electricity in these substitutable applications levelled off, with only the higher share in new construction slowly driving up the total share. In the period 1973–1987, these two kinds of substitution had had roughly equal impacts on fuel choice.

Indeed, part of the decline in delivered energy per household occurred because electricity assumed a larger role in substitutable end uses, eliminating the on-site combustion losses that arise when fossil fuels are employed. Similarly, some of the increase in primary energy use per household occurred because more electricity-using devices were employed. Increases in appliance ownership increased the share of electricity in delivered energy, accounting for two-thirds of the increase in electricity use. These changes mean that aggregate household energy intensity, either on a primary or delivered basis, has limited utility as an indicator of the impact of improved energy efficiency.

We can estimate the impact of shifts in the fuel mix on residential energy use by asking how much fuel and electricity would have been consumed if the share of homes using electricity for space heating, cooking, and heating water in 1987 had been the same as in 1973, but other parameters (the number of homes and the unit consumption of energy-using equipment) had their 1987 values. Under these circumstances, about 0.3 EJ less site electricity would have been consumed, but about 0.97 EJ more fuel. Thus, the increase in primary energy use from this electricity substitution, about 0.95 EJ, was just about offset by the reduction in fuel use of 0.97 EJ. Note again that only part of these shifts occurred through the switching of fuels in existing homes.

Intensity and Efficiency: The Major End Uses

This section analyzes the end uses shown in Figure 13. Useful energy intensities for space heating (in kJ/degree-day/m^2) and major appliances (in kWh/appliance/yr) in 1987 were significantly lower than they were in 1973. Energy intensities of fuel-based cooking and water heating fell significantly, but those for electricity fell less. US homes would have used 39% more fuel and 15% more electricity in 1987 for all purposes than they actually did if these reductions had not taken place. This section reviews these changes.

SPACE HEATING Changes in space heating energy intensity have been dramatic. Weather-adjusted space heating fuel use in 1973 was approximately 7.1 EJ, electricity use 0.2 EJ. By 1987 fuel use fell to slightly under 6 EJ, while electricity use rose to 0.36 EJ. At the same time, the amount of heated floor area increased by nearly 40%. When consumption of principal fuels, as well as LPG and other solids is aggregated, useful energy per dwelling for space heating fell 34%, and 38% per unit of dwelling area. While some of the decline in space heating fuel use was caused by lower home utilization or increased contributions to heating needs by waste heat from other end uses, the changes indicate significant conservation of energy.

Detailed examination of individual heating fuels supports this finding. According to our own tabulations, average consumption of gas in a home using gas for space heating fell by 35% between 1973 and 1987 vs 40% for oil and 26% for electricity. Data from the oil and gas industries (44, 45) show similar declines in sales of fuels for heating, as Figure 15 shows.

There are many causes for these reductions. The thermal characteristics of the external shells of existing homes were upgraded. The number of households adding insulation or other conservation features in 1987 kept pace with or increased slightly relative to earlier years (40, 43). New heating equipment was more efficient than older, too. According to data compiled by the Gas Appliance Manufacturer's Association, the efficiency of new gas furnaces increased from 63.2% in 1972 to 74.7% in 1988. The seasonal coefficient of performance of new heat pumps increased from 2.1 to 2.9 between 1978 and 1988. The gradual replacement of heating equipment in existing homes and installation in new homes has thus contributed to reducing energy use for heating. The share of heat pumps has reached 25% of new homes heated with electricity. Note, too, that part of the reduction in the use of the main space heating fuels, particularly oil, was permitted by a dramatic increase in the use of wood as a secondary fuel.

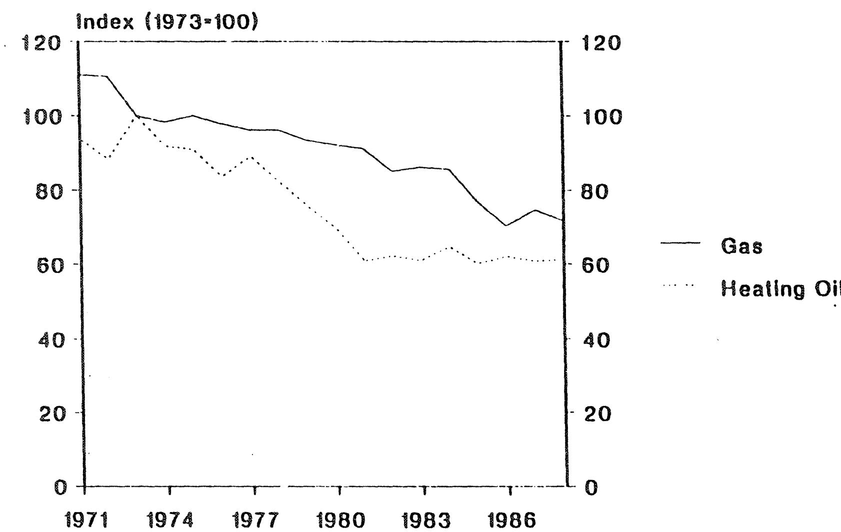

Figure 15 Residential sector. Indices of space heating fuel per dwelling. Sources: oil—*Heating Oil Magazine* yearly survey; gas—surveys from US Gas Association

Efficiency improvements of the building shell in new construction are equally impressive. Meyers (40) compared insulation levels in homes built in 1986 with those built in 1973. The improvement in the nominal thermal resistance of attic insulation was nearly twofold, from R14.4 (or $k = 0.39$ W/deg-C/m^2 in terms of thermal transmissivity) in 1973 to R26.8 ($k = 0.21$) in 1986, and that for wall insulation was less, from R10.0 ($k = 0.56$) to R12.5 ($k = 0.45$). The share of new homes with double- or triple-glazed windows increased from 40% to 79%. In a 1987 snapshot, the fraction of homes with storm windows, wall insulation, and insulated floors over a basement or crawl space is significantly higher in homes built after 1974 than that in homes built before 1974, confirming the new-construction insulation statistics. Similarly, heating equipment efficiency has also improved, as noted above. So energy use for heating in new homes should be significantly lower than that in existing homes.

Data on energy use bear out these improvements in equipment and building shells. Viewed in 1987, gas-heated homes built after 1974 used 20% less gas, as measured in MJ/degree-day/m^2 than those built between 1960 and 1974 (43). Evidently, even though gas heating intensity in these pre-1974 homes has fallen over time, this improvement has not closed the gap in intensity between new homes and the typical home built before 1973. Similar improvements apply to homes heated with electricity and fuel oil. Clearly new homes use less energy for space heating than older ones. Since 24% of the homes in 1987 were built in 1975 or later, this means that improvements in building practices have had an important impact on average heating intensity.

Not all of the reduction in space heating intensity was caused by improved technology, however. Thermostat settings in the early 1980s were several degrees lower than in 1973 (40). By 1987, settings were up slightly over 1984 (43). PNL (2) estimated that the contributions to the reduction in space heating energy intensity between 1973 and 1986 from better equipment and from better building shells in both existing and new homes were about one third larger than the "behavioral" component. Nevertheless, most of the reduction since 1973 is permanent. Only a very concerted effort to induce the raising of thermostat settings well above their 1973 levels would bring heating intensity close to its 1973 value.

WATER HEATING AND COOKING The principal fuels for water heating and cooking are electricity and natural gas, although oil is in some cases still used for water heating, and LPG is used for cooking and water heating in 10–15% of all homes. From 1973 to 1985, the efficiency of new gas water heaters increased only slightly from 47% to 51%, while new electric water heaters improved by a similar fraction. Automatic ignition (i.e. removal of pilot lights) on new gas stoves and clothes dryers has reduced standby losses.

Water use in washing appliances declined significantly, according to figures for dish- and clothes-washers that heat their own water.

It is difficult, however, to determine the changes in actual water heating and cooking energy use caused by improved efficiency. This is because behavior and utilization patterns cause significant changes in estimated or metered end use. Reduced household size, for example, has led to significant declines in hot water use per household; changes in eating patterns as well as additional use of microwave ovens led to lower unit consumption of gas or electricity, for cooking.

ELECTRIC APPLIANCES AND LIGHTING Although electricity use for lighting and electric appliances is not well documented (46, 47), estimates of aggregate electricity use per household for the six most important appliances (refrigerators, freezers, washers and dryers, dishwashers, and air conditioners) give some perspective on the changes that have occurred. Increased ownership of these appliances, had there been no change in unit consumption, would have boosted energy use for these six applications from about 3520 kWh per household in 1973 to about 4250 kWh per household in 1987. Instead, actual use was approximately 3750 kWh per household, representing a savings of approximately 12%, or 0.16 EJ.[10] If this savings rate were applied to all appliances (i.e. all electricity use excluding that for space and water heating and cooking), savings would be about 0.25 EJ.

A variety of studies document the improvements in the efficiency of new appliances sold since 1972 by weighting sales of each product by an indicator of efficiency.[11] Some of these improvements are shown in Figure 16. The improvements are greatest for refrigerators and freezers, smallest for electric water heaters. In general, the improvements are impressive, although further improvements are practical and economic (48).

The reductions in the average electricity consumption of the appliance stock between 1973 and 1986 are less than the improvements in new models, of course, because the turnover in the appliance stock is slow. Moreover, new appliances tend to have more energy-intensive features than appliances being retired (e.g. automatic icemakers in refrigerators). On the other hand, top-of-the-line models often have more energy saving features than simpler models. And average new freezer size declined between 1972 and 1988, while new refrigerator size remained constant after 1978. Finally, there are uncertainties in the estimates of in-home consumption vs laboratory consumption tests of

[10] The unit consumption figures were taken from the Lawrence Berkeley Laboratory Residential Model (J. MacMahon, private communication). The estimated electricity consumption per household for lighting shows a slight decline that can be explained by lower house occupancy (i.e. fewer hours spent at home) and smaller household size.

[11] In the case of refrigerators, for example, this indicator is given by volume per unit of yearly electricity consumption.

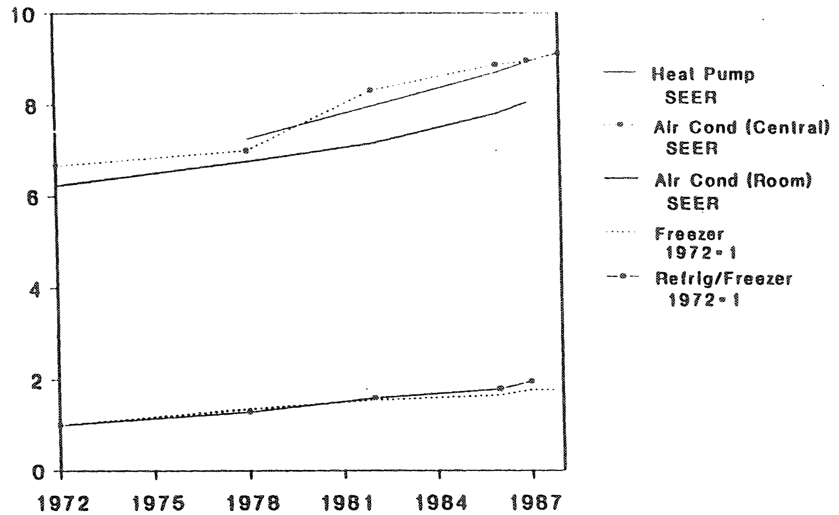

Figure 16 Appliance efficiency trends. Changes in efficiency ratios. These are the shipment-weighted efficiency factors for new electric appliances sold in the United States between 1972 and 1987. For each appliance shown, we display the seasonal energy efficiency ratio (SEER, cooling or heating per unit of electricity consumed) or efficiency (volume cooled per unit of electricity consumption) of all models shipped in the United States in a given year. Source: derived from ACEEE

new models. Thus the 12% reduction in stock-wide unit consumption that we cite represents the combined impact of efficiency improvements and all other factors.

What were the efficiency improvements? Refrigerator insulation, seals, motors, and compressors were improved. Air conditioner motors, compressors, and controls were upgraded. Water requirements for dish- and clothes-washers were reduced. Sensors were added to dryers to shut off heat and power when the moisture in the clothes was low enough. The savings were all achieved using low-cost technology (48).

There is still considerable room for reductions in appliance energy intensity. The average unit consumption of new appliances sold is well above the levels achieved by the most efficient models, and advanced prototypes are even more efficient. It is therefore clear that the present average new intensities do not represent the technically feasible limits of efficiency. And as many argue, these models are also far from limits of economic feasibility (47).

Conclusions: Energy Efficiency in the Residential Sector

The development of energy use in the residential sector is shown in Figure 17. Improved energy efficiency had a clear impact on the residential sector between 1973 and 1987. If only the intensity of fuel and electricity use had

changed while fuel shares, activity, and structural parameters had remained constant at their 1973 values, US homes would have used 6.7 EJ of fuel and 1.8 EJ of electricity in 1987, declines of 27% and 12% respectively from 1973 values. Put another way, reduced intensities alone cut total primary energy use by 21%. Alternatively, had the intensities of each end-use been frozen at their 1973 values, then fuel use in 1987 would have been 10.9 EJ and electricity use 3.6 EJ, yielding total primary energy use of 22.0 EJ, more than 5.7 EJ higher than actual.

Outlook

The energy intensity of a typical new house, heating system, or appliance is by no measure near its theoretical or even economic minimum. Indeed, comparison of average new electric appliance energy intensity with the lowest on the market shows a wide gap. But in some cases the rate of decline in intensity of most new systems has slowed or stopped. It appears that insulation levels in new homes built in 1986 and 1987 were no better than those installed in 1985. The slowdown in efficiency improvements represents a market slowdown, not a bottoming out of technology that is economically attractive (49). The outlook for further decline is therefore dependent on

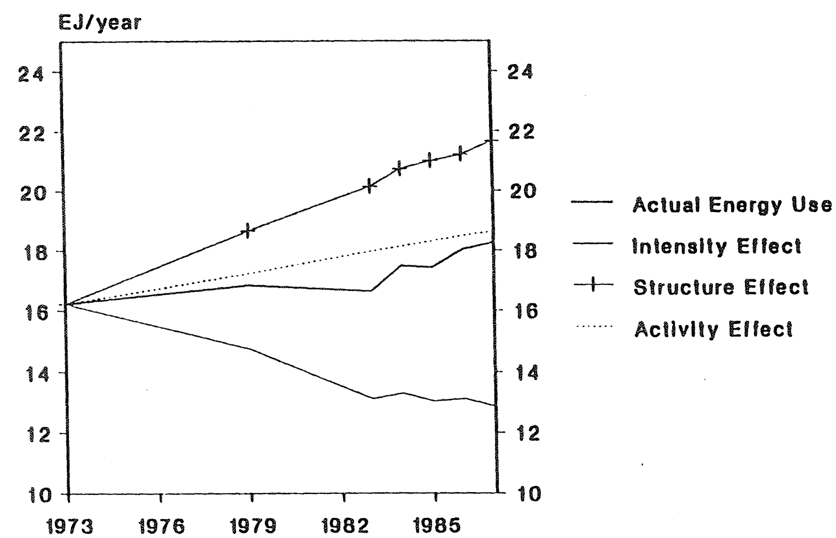

Figure 17 Residential primary energy use. Intensity, activity, structure effects. Evolution of actual and hypothetical primary energy use in the residential sector. Each "effect" is computed by having only intensity, activity, or structure (as defined in the text) follow its actual path while holding the other two components at 1973 levels.

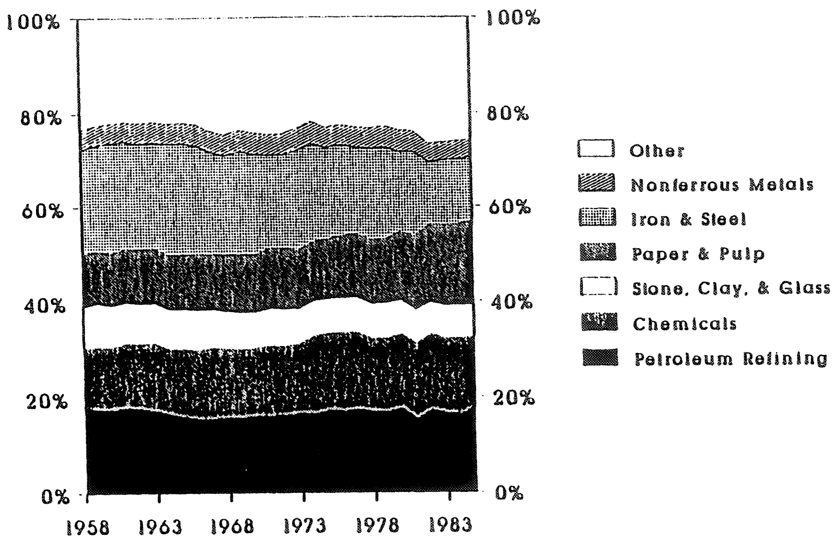

Figure 9 Manufacturing energy use. Shares by industry group.

industry group had remained constant at their 1973 values while the proportion of output produced by each industry followed its historical development. We found that structural change had no significant impacts on energy use between 1958 and 1973. Between 1973 and 1985, however, structural change at constant output and energy intensity would have depressed energy use by 18%, or 1.6% per year (Figure 10).

The impacts of structural change were driven largely by a decline in the proportion of output produced in coal-intensive industries—particularly the iron and steel sector, which alone accounts for one-third of manufacturing coal consumption. While structural change would have reduced coal use by 33% between 1973 and 1985, the corresponding reductions in oil, gas, and electricity use were 16%, 16%, and 10% respectively. These results suggest that rising oil prices were not the most important factor driving structural change. A number of analysts have suggested that a long-term reduction in the materials intensity of the US economy that has significant energy implications has been under way (28). Indeed, the physical production of certain raw materials such as steel fell significantly during the 1970s and 1980s, although the production of other commodities such as plastics increased (29). But other factors, such as macroeconomic policies that have given rise to high interest rates and a strong dollar that have placed the US raw materials sector at a comparative disadvantage, have also been important. Over the one-year period 1981–1982, for example, the output of the iron and

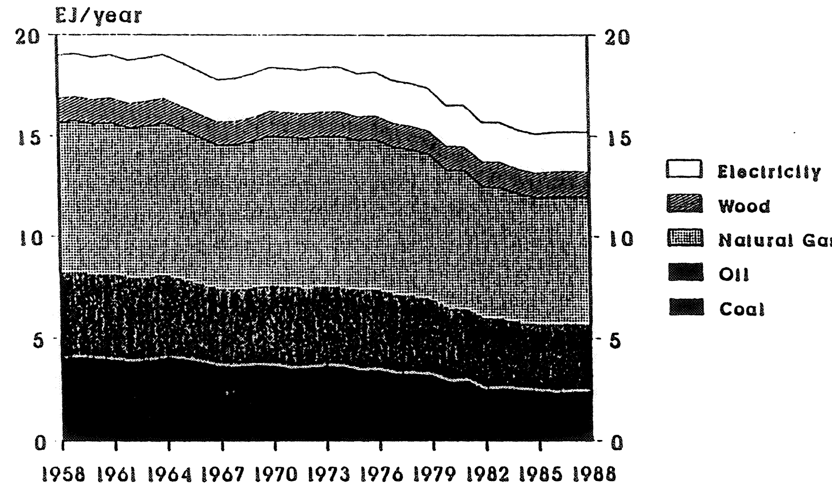

Figure 10 Manufacturing energy use. Impacts of structural change. This shows the hypothetical evolution of energy use in manufacturing if activity and intensities had remained constant at 1973 levels and only the value-added shares of the subsectors (structure) had followed their actual paths.

steel sector fell by 37% during the strong recession. This change alone yielded an energy use reduction of 1.1 EJ, or 7% of manufacturing energy use.

Structural change had no measurable impacts on energy use between 1985 and 1988, either in aggregate terms or on a fuel-by-fuel basis, at the level of aggregation employed in this analysis. In recent years, raw materials production, as measured in economic terms, has kept pace with aggregate manufacturing activity. These results suggest that the expectation that shifts in the composition of manufacturing value-added away from energy-intensive industries will lead to significant future energy savings may not be fulfilled, or at least that the anticipated decline may not be smooth and continuous.

The rate at which manufacturing output grows over time is also an important determinant of sectoral energy use. Real manufacturing value-added grew at the rapid rate of 5.4% per year between 1958 and 1973 and at the slower but still substantial rate of 2.7% per year between 1973 and 1988 (Figure 8). Thus sectoral growth placed strong upward pressure on energy use throughout the period of analysis. Changes in the growth rate of manufacturing production relative to GNP are a structural effect of particular relevance to manufacturing energy use. But while some analysts have argued that the economic importance of manufacturing has declined significantly over time, the data point to a different conclusion. The fraction of real US GNP generated by the manufacturing sector remained more or less constant at 21% in the 1970s and 1980s with only minor changes induced by business cycle future forces that affect the marketplace—residential energy prices, the perceived or real incremental benefit of greater efficiency, and public policy.

One important policy that will raise efficiencies is the National Appliance Efficiency Standards, which take effect initially for refrigerators, freezers, water heaters, and room air conditioners in 1990. More stringent efficiency requirements for refrigerators and freezers will take effect in 1993, and requirements for other products are likely to be upgraded in the future as well. California, one of the largest economies in the world, has upgraded its own requirements on the efficiency of household appliances sold in the State, too. This type of policy circumvents consumers', manufacturers', and builders' high implicit discount rates, as well as a variety of other market and nonmarket barriers to more efficient energy use.

Moreover, there are a number of important energy-saving technologies that are starting to penetrate the market to a significant degree (18, 49). These include low-emissivity glass for windows, vastly improved gas furnaces and gas heat pumps, and electric heat-pump water heaters. As for the future of very efficient refrigerators, freezers, and air conditioners, progress here is clouded by uncertainties over future refrigerants (50). Finally, novel wall constructions and building techniques, as practiced almost universally in Sweden (51), promise to reduce heating losses in new detached housing markedly. A further decline in energy intensity should occur as these new technologies are more widely disseminated, as ongoing R&D leads to ever better technologies (such as gas-fired heat pumps), and as appliance and building standards take effect and are improved.

SERVICE SECTOR

The energy use of the service sector is dominated by building-related activities (52). Survey data on energy use, floor area, and other characteristics of the US service sector are available only for 1979, 1983, and 1986 (53). From other data (SEDS) (54), which include energy use for activities not associated with building energy use, Schipper et al (52) assembled a time series of energy use data that can be adjusted to match the 1979 and 1983 surveys. The results for key years are shown in Figure 18. Delivered energy use rose from 5.3 EJ in 1973 to 5.9 EJ in 1979—a very cold year, then fell to a plateau of 5.3 EJ in 1986. Primary energy use, on the other hand, rose from 8.8 EJ in 1973 to 11.1 EJ in 1986, as a result of the substitution of electricity for fuels and further penetration of electricity-driven services like computers and lighting.

The Structure of the Service Sector

Service sector GNP, excluding utilities, grew nearly 50%, from 1.67 trillion dollars in 1973 to 2.51 trillion in 1987 as evaluated at 1982 prices. We take

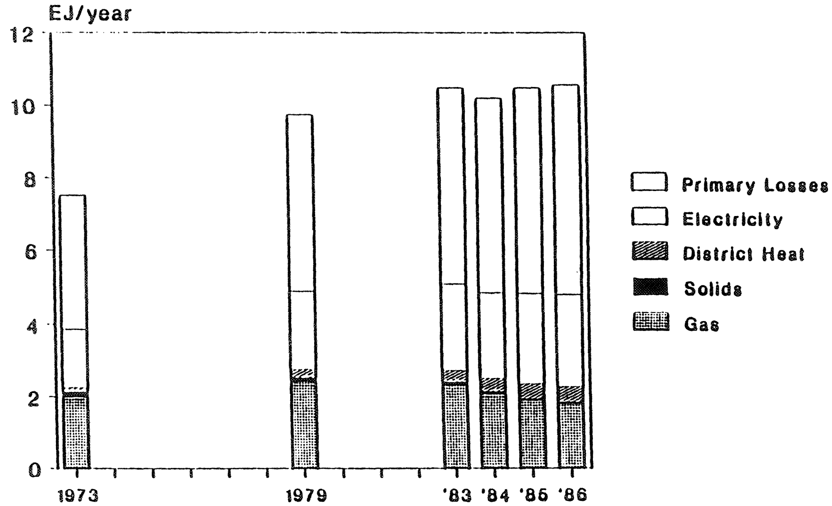

Figure 18 Energy use in service sector buildings by fuel type. Sources: SEDS, NBECS.

these figures as the indicators of the change in sectoral activity over the period of the analysis. The structure of the service sector can be measured by several quantities. The most important is floor area, which grew from an estimated 3.5 billion square meters in 1973 (52) to more than 5.4 billion square meters in 1987 (53). This growth was only slightly faster than the growth in service sector GNP. However, the ratio of sectoral floor area to total GNP increased because the share of service sector GNP in overall GNP increased from 61% to 65%.

Additionally, the mix of buildings changed slightly. According to PNL (2), the share of office building floor space increased from 16.6% in 1972 to 19.8% in 1986, and shares of warehouses and lodging increased slightly. Shares of retail, food sales, and educational floor space fell, the latter significantly, from 16.1% to 13.9%. And the geographical distribution of buildings shifted slightly towards the South and West. According to PNL, the mix effect increased fuel and electricity use by about 0.08 and 0.06 EJ, respectively, while the geographical shift reduced fuel needs by 0.04 EJ but increased electricity use by 0.02 EJ. Thus the impact of structural change, as measured by the slight increase in the floor area per unit of service sector GNP, changes in the mix of buildings, and geographical shifts, is very small compared to total fuel utilization of 2.5 EJ and electricity use of 2.5 EJ in 1986. By contrast, the activity effect was significant because the service sector GNP grew 7% more than total GNP. Yet between 1973 and 1987, service sector energy use increased by only 5%, while primary energy use grew by 27%.

The structural change reported here does not include shifts in the kinds of energy services provided in buildings, particularly those relying on electricity. The share of floor space provided with cooling, and the level of use of computers and other communications equipment has increased markedly. These shifts increased electricity use. Some of the waste heat from this electricity use reduced space heating needs in winter months but increased cooling needs during the rest of the year. Hence a broader view suggests that the overall impact of structural change on energy use in the service sector has reduced fuel use slightly for heating but increased electricity use significantly for a variety of purposes.

Fuel Mix

The mix of fuels in the service sector has evolved in a manner similar to that of the residential sector, away from oil and towards electricity. Driving the increased share of electricity was both further electrification (i.e. more uses of electricity), as well as greater penetration of electric heating. Measured by the area of buildings they heated, heating fuels chosen were predominantly oil (22%) or gas (50%) in 1979.[12] From NBECS data on heating fuels in buildings built before 1973 we infer that the share of area heated by electricity grew steadily, from, approximately 7% of the entire stock in 1973 to 15% in 1979 and 21.5% in 1986, while those of gas or oil (and LPG) have decreased from an estimated 87% in 1973 to 67% in 1986. Part of this shift towards electricity as the principal heating fuel is explained by the shift of service sector activity towards warmer climates, where lower heating loads permit electric heating to compete better against gas or oil.

Intensity and Efficiency

Measuring changes in energy efficiency requires the disaggregation of energy use into end-uses, such as space heating or cooling. But the services provided by energy in the service sector are diverse and changing. With current data gathering efforts, it is very difficult to break energy use by fuel into end uses, and it is therefore very difficult to derive energy intensities for each purpose in order to gauge the impact of improved efficiency.

It is possible, however, to estimate how energy use per unit of floor area has changed. Since surveys have measured energy use and intensity only since 1979, comparing present-day intensities with those from 1973 is problematic. The imprecision of the SEDS (54) data compound this problem.

[12]NBECS (53) did not distinguish between primary and secondary heating fuels. We took the share of buildings using each fuel over the sum of the shares, which was 114%.

Nevertheless, Schipper et al (52) found a 16% decline in delivered energy use per unit of floor area between 1973 and 1983; extending the data from that report to 1986 (to compare with NBECS) and extrapolating to 1987 yields an overall reduction of 33%. The intensity of fuel use, including district heat, fell 49%. About half of this decline was likely caused by reductions in the proportion of floor area heated by fossil fuels and by the very mild winter of 1987. We can compare energy intensity in 1979 and 1986 by building type. Figure 19 shows that delivered energy per unit floor area declined for most building types. The same is true for fuel intensity, electric intensity, and primary energy intensity.

Most fuel is used for space heating, with a small amount of fuel used for water heating and cooking (55). Most observers allocate as much as 80% of fuel use to space heating. We believe, therefore, that comparing fuel (and district heating) use to the estimated area heated by fuel provides one meaningful measure of energy intensity. By our estimate, heating intensity lay at 940 MJ/m^2 in 1973, falling to 790 MJ/m^2 in 1979 and further to 560 MJ/m^2 in 1986. Even allowing for uncertainties in weather correction, the share of fuel used for heating, and the share of buildings with fuel heat in 1973, the magnitude of this change is a clear indication of significant savings of space heating fuel.

Some more precise measures of intensity changes are available from NBECS. Gas use per unit area in buildings heated with gas, for example, was 981 MJ/m^2 in 1979 as compared with 555 MJ/m^2 in 1986. Although use of

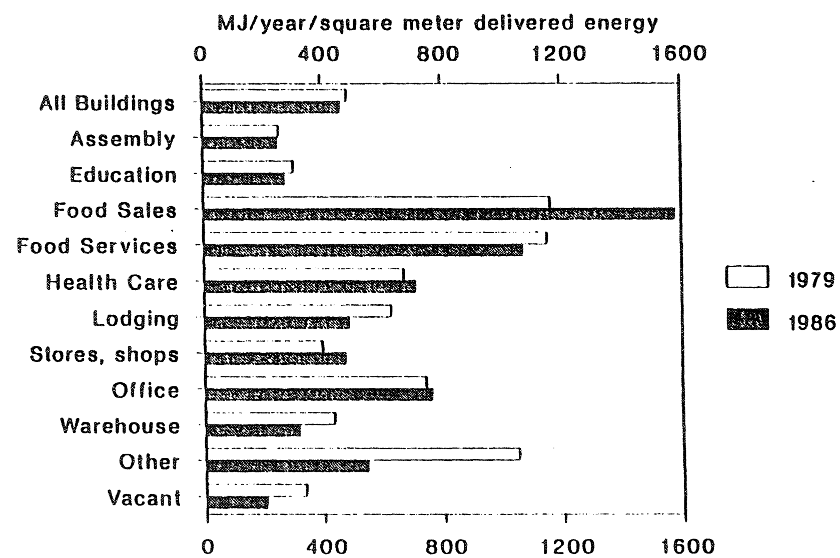

Figure 19 Service sector. Changes in energy intensity by subsector. Source: Ref. 53

secondary fuels may account for part of this drop, increased efficiency is evident. Figures for oil heat show a similar decline. The fuel intensity of most building types also fell between 1979 and 1986. Since most fuel was used for space heat, this evidence points towards a significant savings of space heating.

Electricity is more problematic, because the only use found in every building is that for lighting. Available data do not permit a comparison of electricity use by end-use over time. Electricity intensity in buildings that heat with electricity fell from 650 MJ/m^2 in 1979 to 579 MJ/m^2 in 1986, about the same percentage reduction as the change in the number of heating degree-days. Thus it is difficult to draw conclusions about the intensity of electric heating. The same applies to cooling. On the other hand, total electricity intensity, aggregated over all buildings, remained constant between 1979 and 1986. Since the penetration of electric heating, cooling, and other equipment (e.g. computers) increased, this implies that some improvements in the efficiency of electricity utilization must have occurred.

Combining the limited knowledge we have concerning the use of individual fuels suggests that the reduction in fuel intensity between 1979 and 1986—almost 37%—was caused principally by efficiency improvements, but increased penetration of electric heating captured about 5% of the heated floor area between 1979 and 1986, and the milder climate in 1986 alone allowed a reduction in heating needs of about 10%. The remaining decline, approximately 25%, can be ascribed to saved fuel for space and water heating.

The PNL analysis (2) attempted to quantify the factors that caused intensity to fall. Although it found more than 80% of its "conservation" effect unexplained, it judged that factors other than improvements in building shells accounted for much of the savings. Building shell retrofits accounted for 7% of the savings, and the high efficiency of new buildings relative to the existing building stock for an additional 8.5%. The location of more buildings in warmer climates had a minor effect. A shift in building type also contributed to the decline in fuel use. PNL, on the other hand, omitted explicit reference to the shift towards electricity as a primary and secondary heating source. Our estimate of the share of electric heating in 1973, 7%, implies a loss of more than 14 points in the share of fossil-fuel heating, which by 1986 should have reduced fossil fuel intensity over all buildings by nearly 10%, accounting for part of PNL's unexplained residual. We estimate that whereas only 0.1 EJ of electricity was used for heating in 1973, the figure increased to 0.32 EJ in 1986; cooling electricity use increased from 0.27 EJ in 1973 to 0.42 EJ in 1986.

Conclusion: Energy Efficiency in the Service Sector

How much energy was saved in the service sector between 1973 and 1987? We showed that relative to overall GNP, service sector GNP and total

building area increased slightly, increasing sectoral energy use. Fuel shifts reduced fuel needs but increased needs for electricity. Although our figures are rough, we believe that a 40% decline in fuel heating intensity and an 18% decline in electric heating intensity took place. These improvements yielded savings of approximately 1.5 EJ of fuel and 0.07 EJ of electricity, as compared with actual utilization of 2.16 EJ and 0.33 EJ, respectively. Finally, the increased share of electric heating raised electricity use by approximately 0.15 EJ but reduced fossil fuel use by roughly 0.6 EJ.

Outlook

A number of studies (18, 49, 55, 56) suggest that the intensity of virtually any new system or energy service can vary considerably. New lighting systems, supported by specular reflectors, electronic ballasts, and judicious use of daylighting, have reduced electricity intensity for lighting by 50–75% in some commercial buildings (55). Low-emissivity glass can reduce heat losses or gains significantly, yet allow for maximum use of daylight to reduce artificial lighting loads as well. Variable speed/volume space-conditioning systems offer reductions in power for motors and compressors without reducing comfort; air-to-air heat-exchangers allow for higher indoor air quality with substantial heat-loss reductions. Interestingly enough, the trend towards designated smoking areas could also lead to a reduction in ventilation needs, as smoke-free areas require far fewer air exchanges than areas where smoking takes place.

National surveys as well as information from equipment manufacturers indicate that various energy-saving technologies are starting to be adopted on a large scale. For example, the national survey of commercial buildings conducted by the US Department of Energy showed that high-efficiency ballasts had been implemented in 42% of new commercial floor space, delamping programs had been implemented in 21% of commercial floor space, and energy management and control systems had been implemented in 19% of commercial floor space as of 1986 (53). These and other technological improvements contributed to the decline in energy use per unit of floor area during 1973–1986.

Continuing technological improvements in lighting, space conditioning, and other end-uses will limit future growth in energy use in the service sector. These improvements are being stimulated by market forces as well as government and utility programs. For example, the federal government adopted minimum efficiency standards for new fluorescent lighting ballasts. These standards, which took effect January 1, 1990, are expected by the year 2000 to reduce electricity utilization in commercial buildings by around 0.1 EJ/yr (equivalent to 4% of electricity use in commercial buildings in 1988 (57). Minimum efficiency standards for fluorescent and incandescent lamps are being adopted in Massachusetts (58), and lamp efficiency standards are under consideration in other states as well as at the federal level.

In 1989, the US Department of Energy issued minimum efficiency standards for new commercial buildings (59). These standards are mandatory for federally owned buildings but voluntary for the private sector. States that follow these guidelines by revising their building codes could significantly reduce energy use in the services sector over the long run. For example, models suggest that new office buildings meeting these standards would use 15–30% less primary energy than buildings complying with standards widely adopted in the early 1980s (55).

Concerning utility programs, many utilities provide financial incentives such as rebates to stimulate the adoption of energy-efficient technologies in the service sector. A few utilities even install energy-efficiency measures at their own expense on the premises of their customers. The most effective utility programs are reaching 70% or more of eligible customers and are reducing electricity use by 10–30%, although most utility programs are not nearly this successful (60). The overall impact of utility energy-efficiency programs is expected to grow as more utilities implement full-scale programs, programs are improved, and the goal of "least-cost energy services" spreads throughout the utility industry.

One technological trend—the proliferation of electronic office equipment—could significantly increase future energy use in the services sector. Saturation of personal computers, printers, copiers, fax machines, etc is expected to continue growing during the 1990s. One study estimates that without efficiency improvements, total electricity use by office electronic equipment could climb by 160–360% between 1988 and 1995 (61). However, full use of today's most efficient hardware could potentially eliminate all of this electricity demand growth. Thus, with uncertainty regarding both the rate of growth and the efficiency of new electronic equipment, it is difficult to predict future energy use in the services sector.

CONCLUSIONS AND DISCUSSION

The Impacts of Improved Efficiency

Figure 20 shows the evolution of primary energy use from 1973 to 1987 (see also Table 1). We give actual primary energy use measured for the sectors we have considered,[13] and the three hypothetical levels of primary energy use

[13]We omit consideration of the residual between total primary energy use as reported by DOE (5) and the primary energy used in the sectors considered in this analysis. It is unlikely that the evolution of the residual between our figures and those given by DOE—from 12.6 EJ in 1973 to approximately 11.6 EJ in 1987—has an important impact on our results.

that would obtain if only energy intensities, only sectoral activity levels, or only intrasectoral structure had changed over time while the other two factors were held constant at their base-year (1973) values. The impact of changing energy intensity is almost equal and opposite to that of activity, while structural change led to modest increases in energy use. Thus reduced energy intensities had a major impact on US primary energy use.

Figure 21 summarizes the impacts of structural changes on US energy use by sector between 1973 and 1987. All figures are indexed relative to their 1973 values. It can be seen that only in the service and manufacturing sectors did sectoral activity grow more rapidly than GNP. Intrasectoral structural change, on the other hand, placed substantial upward pressure on residential energy use; had relatively small effects in the service, freight, and passenger transport sectors; and yielded significant energy savings in manufacturing. Taken together, the impacts of changes in both activity and structure exerted a small upward influence on energy use relative to GNP in the residential and service sectors and a small downward influence in the freight, passenger transportation, and manufacturing sectors. In the aggregate, increased activity levels and structural change would have increased delivered and primary energy use by 35%. Actual energy use, on the other hand, decreased by 2% in terms of delivered energy, and increased by only 6% in terms of primary

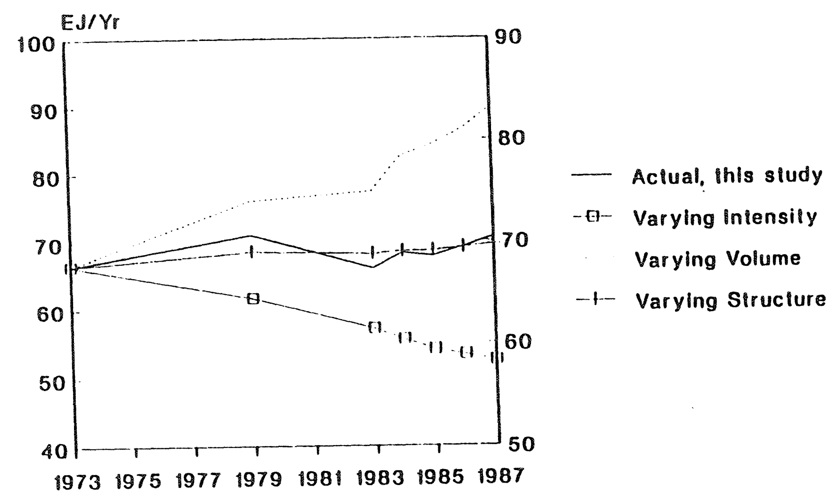

Figure 20 Primary energy use. Evolution of actual and hypothetical energy use in the five-sector aggregate. Each "effect" is computed by having only intensities, activity levels, or structure (as defined in the specific sectors) follow its actual path while holding the other two components constant at 1973 levels. Definitions of these components are given in the respective chapters. Fuel and electricity figures from each activity sector are summed counting electricity being at 11,500 Btu or 12616 kJ per kWh to account for conversion losses. Sources: DOE, LBL

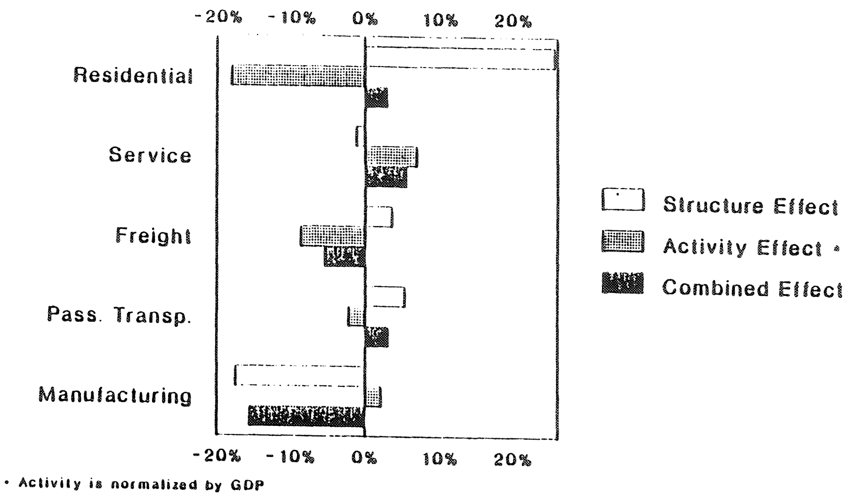

Figure 21 Changes in delivered energy use since 1973. Activity and structure effects. Hypothetical 1973–1987 changes in energy use if only sectoral activity level per unit of GNP (activity effect) or the composition of activities as defined in the respective sectors (structure effect) had followed their actual paths while all other factors had remained constant at 1973 levels. The net effect captures the combined impact of changes in the mix and level of activities in each sector relative to GNP.

energy. In either case, the divergence between the two sets of figures is an indication of the substantial impacts of improved efficiency on US energy use.

Which sectors showed the greatest reductions in energy intensity? Figure 22 shows how structure-adjusted energy intensity, in terms of both delivered and primary energy, evolved over time in each end-use sector. The declines varied from 31% in manufacturing to 20% in passenger transportation to 4.5% for freight. (In primary terms, the percentage declines were less except for transport, where they were the same.) These declines together point to a reduction in aggregate energy intensity between 1973 and 1987 of the sectors considered in this report of 24% in terms of delivered energy or 21% in terms of primary energy. These improvements correspond to net savings of 16.5 EJ of delivered energy and 19.7 EJ of primary energy at 1987 activity levels. That delivered energy intensity fell more than primary reflects the fact that fuel intensity fell by 26% while electricity intensity fell by only 8%.

We can also highlight the activities where the most unambiguous efficiency improvements occurred: passenger air travel energy intensity declined by nearly 50%, residential and services space heating intensity by about 35%, and manufacturing fuel intensity by about 34%. Automobile and light truck vehicle fuel intensity fell by 28%, but falling load factors offset this improve-

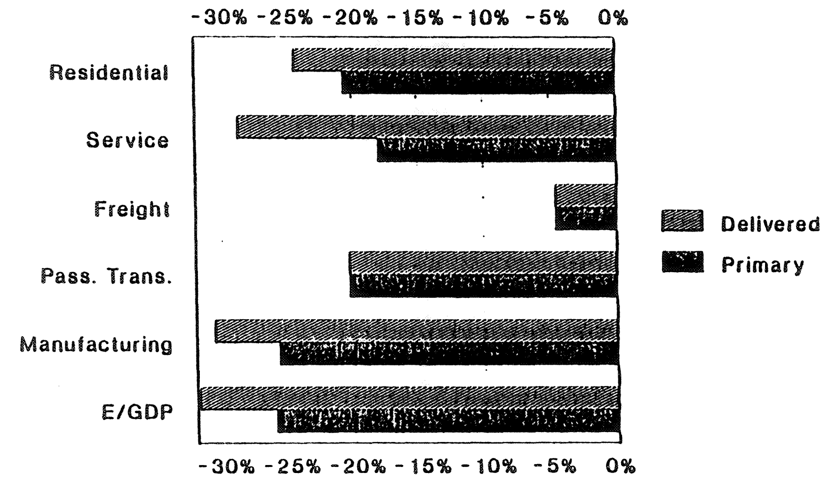

Figure 22 Changes in delivered energy use since 1973. Energy intensity effect. Hypothetical 1973–1987 changes in primary and delivered energy use if only energy intensities had followed their actual paths while sectoral activity levels and structure had remained at 1973 levels.

ment in travel efficiency. The intensity of electric appliances declined by some 12%.

Several factors served to increase energy demand, thereby offsetting in part the impact of these improvements. Truck freight intensity increased, in part because of the rise in short-haul light trucking. Changes in the modal mix of passenger transportation raised energy use slightly. Heated residential floor area, and the number of appliances per household, increased. Changes in the kinds of services offered in commercial buildings, particularly those using electricity, raised energy use. Structural change in the manufacturing sector, on the other hand, led to reductions in the production of energy-intensive bulk materials relative to other products.

Since the energy/GNP ratio is sensitive to all factors affecting energy use, not just those that are conceptually related to energy efficiency, it is a misleading efficiency indicator to the extent that structure and activity have important effects. On balance, structural change and growth in sectoral activity levels served to raise the level of energy use. But the growth in energy use induced by these factors was smaller than the increase in GNP, so that changes in the level and structure of sectoral activities led to net reductions in the energy/GNP ratio over the period of analysis. The reduction in the primary energy/GNP ratio between 1973 and 1987 therefore overstates the efficiency improvement that occurred over the period, perhaps by as much as one-fourth of the total reduction in the ratio.

The Efficiency Slowdown

Figures 20 and 22 show that improved energy efficiency had a considerable impact on total US primary energy use. Data from the last several years, however, suggest that the rate of efficiency improvement implied by our sectoral analyses may be slowing down or even coming to a halt. The drop in world oil prices in 1986 has begun to have an impact on energy intensities. The energy intensities of some classes of energy-using equipment, such as new automobiles, are no longer decreasing over time. In some applications, energy intensity is even increasing.

In the residential sector, primary and useful energy use per household declined through 1983 but have increased in more recent years. Heating intensity, which had fallen by 4.5% per year through 1983, fell by less than 1% per year between 1983 and 1987. Adjusted for structural change, primary energy intensity also fell more rapidly before 1983 than thereafter. By contrast, the rate of decline in appliance energy intensity increased after 1982, and should continue to fall because new appliances are more efficient than older ones.

In the service sector, the decline in fuel heating follows the same pattern as space heating in homes, while the increase in nonheating electricity intensity before 1983 turned to a decline after that time. Structure-adjusted primary energy intensity in services thus falls more rapidly after 1983 than before, although the decline appears to bottom-out after 1985. These observations suggest that efficiency increases in buildings have slowed, although the impact of more efficient electricity use is delayed as the impact of new equipment is still being felt in the stock.

The transportation sector shows an intensity plateau, too. The specific fuel utilization of personal vehicles fell more rapidly before 1983 than in more recent years. This is due to the rapid growth in light trucks during the late 1970s and early 1980s as well as the relaxation of federal fuel-economy standards in recent years. The combined fuel intensity of new cars and light trucks fell by 6.2% per year before 1983 but by only 1.3% per year thereafter. Passenger energy intensities as measured in MJ/passenger-km fell less rapidly because of the decline in load factors. Air passenger intensity fell more rapidly before 1983 than from 1983 to 1985, but the decline accelerated again after 1985. Significantly, the improvement in air and automobile passenger fuel intensities was most rapid during the period of rapid activity growth. This makes sense: growth in activity implies investment in newer, more efficient vehicles and higher load factors on planes. Together, these effects lower the average passenger intensity of the transportation sector. For freight, all indicators point to more rapid progress before 1983 than thereafter; the ORNL data, for example, show that no substantial improvements in truck fuel economy have been achieved since 1982.

In the manufacturing sector, on the other hand, there is less evidence of a slowdown in efficiency improvements. As in passenger transportation, manufacturing energy intensity is strongly dependent on changes in sectoral activity. Energy intensity, adjusted for structural change, increased at annual rates of 0.3% and 2.2% during the recession years 1980 and 1982. But in years with strong sectoral growth, energy intensity has fallen very rapidly. Between 1983 and 1985, for example, energy intensity fell at an average rate of 6.2% per year—more than twice the long-term average annual rate of 2.7%. These fluctuations are presumably caused by two factors. First, decreased capacity utilization during recessions leads to the inefficient use of energy inputs. Second, sectoral growth permits investment in new, relatively efficient technology. The response of manufacturing energy intensity to the drop in energy prices in 1986 is difficult to gauge in the absence of manufacturing energy use data past 1985. As we noted above, the aggregate energy intensity of the industrial sector, which is dominated largely by manufacturing, decreased by 2.9% between 1985 and 1986 but remained almost constant between 1986 and 1987. But energy-intensity statistics from the iron and steel, paper and pulp, and chemicals sectors indicate continuing reductions in energy intensity of 1.7 to 4.1% per year.

When we assemble a picture from each sector, the results are rather surprising. Structure-adjusted energy intensity fell by 2.35% per year after 1983, but only 1.8% before. For primary energy intensity, the figures are 2.0% and 1.5%. Significantly, however, intensity fell by only 1.7 and 1.5% between 1985 and 1987. Thus the overall impact of energy-efficiency improvements was most rapid between 1983 and 1985, a period of economic recovery and flat or declining real energy prices.

We have not discussed energy prices in detail in this review. It is worth noting that between 1973 and 1983, real prices for natural gas grew at average rates of 7.4% and 13.1% per year in the residential and industrial sectors, respectively, electricity prices grew by 2.3% per year in the residential sector and 5.7% per year in the industrial sector (5); and regular gasoline prices rose at an average rate of 8.6% per year. Between 1983 and 1987, however, all of these prices declined in real terms. Residential heating oil prices behaved similarly. That real prices were declining when intensity was falling the most rapidly seems counterintuitive. Yet we have suggested that time lags in the system, as well as the poor state of the economy in the early 1980s, retarded the replacement of inefficient equipment, and likely slowed investment to improve existing equipment as well. The effect of this improvement was swamped, however, by the dramatic crash in prices after 1986, although it is too early to judge the more long-term effects.

Implications for Future Energy Use

Are the energy savings that have been achieved over the past 15 years permanent? The rapid savings in space heating through 1983 may have been bolstered by short-term sacrifices that could wear off with lower prices. But the savings that accumulated after 1983 were likely achieved through technical improvements that are unlikely to be reversed in the near-term future. Savings in electricity use in the service sector also appear to be technologically based, and therefore not easily reversible. Savings in personal vehicles were almost totally due to technology, not reduced driving distances. Even if new-car fuel economy remains stable at its present value (27 to 28 mpg nominal, 22 to 23 mpg actual), it still lies 20% above the on-road fleet average. The savings in manufacturing may represent only the extension of a long-term trend, and therefore might be considered permanent.

At the same time, we must not overlook the implications of the slowdown in energy-efficiency improvements, which has appeared primarily in those sectors dominated by consumers: driving and household energy use, and services. Similarly, the rapid growth in the activity levels of the service and passenger transport sectors must be borne in mind. As Schipper et al (42) suggest, increases in free time could drive up energy uses for thes purposes, as well as for the private vehicle travel associated with out-of-home services. That is, a combination of the slackened improvement in efficiency indicated by the slowdown and continued growth in the volume of key end-uses—structural change—could propel energy uses upward once again.

A return to growth could pose significant policy problems in light of scientific concern over the role of fossil fuel combustion in global climate change (62). If efficiency improvements slow down while structural change increases energy demand further, then policy makers will have to work harder to restrain the emissions that result. If increased demand takes up the slack in world oil markets, the world's economies may see a repeat of the roller coaster of the 1970s and 1980s. Technological progress fostering a return to improved energy efficiency might head off one or both of these possible dilemmas. As Carlsmith et al (18) and Hirst (49) point out, the technical, economic, and policy opportunities are enormous. But as Schipper (63) warned, policies may have caused only a small increment in the total savings in the industrialized countries through 1985. Achieving the potential savings documented in the literature through the implementation of appropriate policies will be the challenge of the 1990s and beyond.

NOTE ADDED IN PROOF Preliminary analysis of yet unpublished data for 1988 indicates that fuel intensity, adjusted for structural change, fell by 6.0% (2.0% per year) between 1985 and 1988; electricity intensity fell by 10.8% (3.8% per year); and total energy intensity fell by 6.6% (2.3% per year). These results generally confirm the approximations used in this section.

ACKNOWLEDGMENTS

This work was carried out with the support of the US Environmenal Protection Agency and the US Department of Energy, as well as several private funding sources. We acknowledge the contributions of Stacy Davis of the Oak Ridge National Laboratory, who kindly provided much assistance in interpreting the ORNL transportation data, and Sarita Bartlett and Peter Duerr, who assisted in the preparation of these data. Steve Meyers made available to us detailed data on residential energy use and commented extensively on the manuscript. Finally, we acknowledge thoughtful comments by Arthur Rosenfeld, Marc Ross, and Rob Socolow.

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