# THE ROLE OF FEDERAL R&D IN ADVANCING ENERGY EFFICIENCY: A $50 BILLION CONTRIBUTION TO THE U.S. ECONOMY

Howard Geller, Jeffrey Harris[1],
Mark Levine[2], and Arthur Rosenfeld[2a]

1987

American Council for an Energy-Efficient Economy
1001 Connecticut Avenue, N.W. #801
Washington, D.C. 20036

[1]U.S. Department of Energy
Washington, D.C.

[2]Lawrence Berkeley Laboratory
Center for Building Science
Berkeley, CA

## Table of Contents

# PART A.

## INTRODUCTION

- **Increasing energy efficiency is an important national goal.** Improved energy efficiency can sharply cut the $400 billion annual energy bill for our economy, buy us time to diversify our long-term energy options, reduce dependence on energy imports, improve national security, and mitigate a number of environmental problems.

- **We have already made huge gains in reducing energy use per dollar of GNP.** If today's economy consumed energy at the rate of the 1973 economy, we would be importing twice as much oil and spending an extra $130 billion per year for energy.

- **The economy can still achieve large, cost-effective improvements in energy efficiency,** both by using technology that has evolved in recent years and by taking advantage of technological opportunities that will result from ongoing research. We can add to the gains of the past decade; engineering analyses indicate significant opportunities for cost-effective energy efficiency measures in all sectors of the economy.

- While the private sector has played a key role, in some areas, as in jet aircraft engines, **most energy conserving innovations can be tied to federal R&D programs,** which can contribute even more in the future. Case studies show that federal support for developing and advancing commercial adoption of new conservation technologies has saved billions of dollars for industry and consumers. For seven case studies presented in Table 1, federal investments totaling $16 million will generate savings of $63 billion in the years by which the federal government advanced commercialization of new technologies. This represents a return on the taxpayers' investment of 4400 to 1! Of course, not all R&D efforts can produce such dramatic payoffs, but even if these seven projects had to justify the entire federal investment in energy conservation R&D over the past decade, they would represent a 50:1 return.

- **Continued advances in energy-saving technology can play a key role in ensuring the competitiveness of U.S. industry** in the world market not only by enhancing industrial productivity, but also by leading to the development of new, highly valued products for U.S. and international markets. Experience shows that well-conceived federal R&D can reinforce private industry initiatives. Conversely, a lack of federal support may open the way for aggressive firms overseas--often with their own governments' backing--to gain the edge in both U.S. and world markets.

- **The federal government has a vital role in carrying out energy conservation research, development, and technology transfer.** Without active federal participation, important technological advances would often be hampered by industry fragmentation, market structure, or the noncapturable ("public good") nature of basic research. U.S. industries and consumers both benefit directly from energy conservation R&D, but if the federal government withdraws, the private sector cannot take up all the slack.

- **Federal energy conservation R&D has contributed significantly to the underlying policy objectives of the Gramm-Rudman-Hollings legislation** by reducing the need for expensive, new energy production systems and thus easing pressure on capital markets. Future energy conservation R&D will yield additional technologies that can reduce the need for additional energy supply facilities.

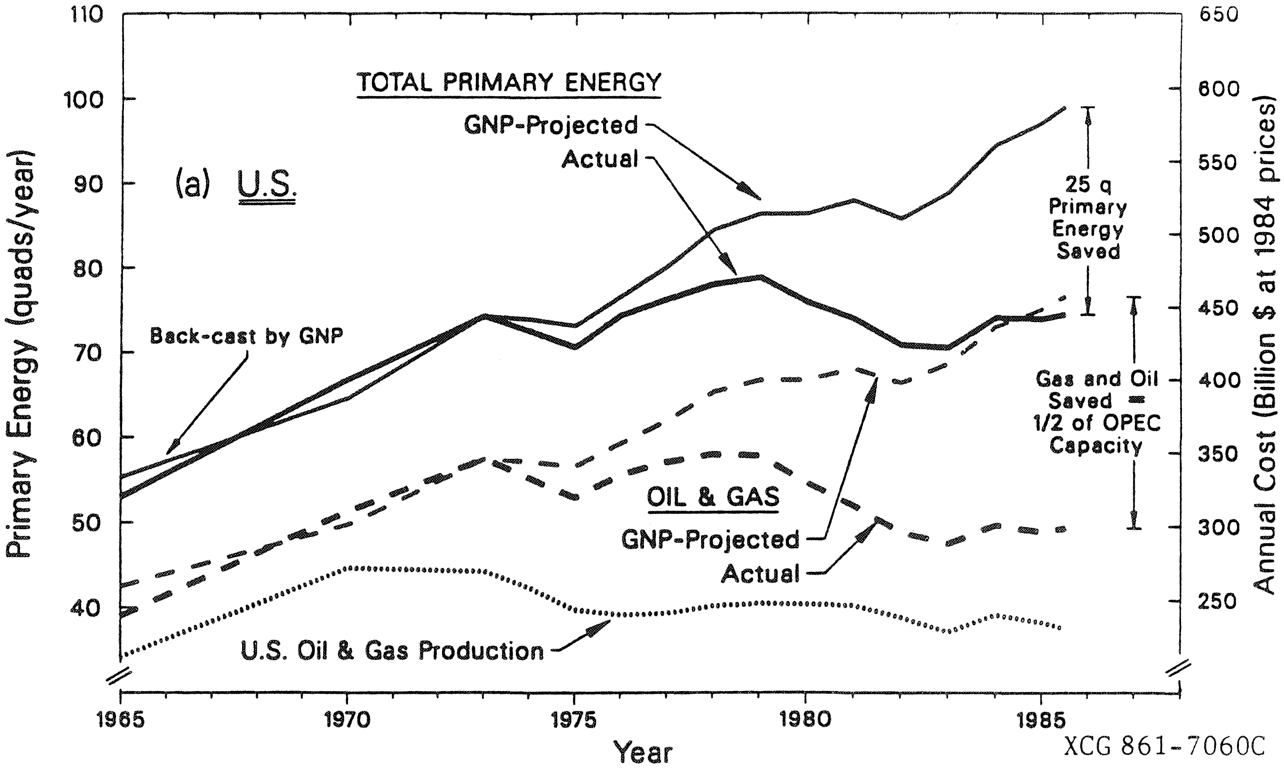
These views are strongly supported by the recent report, Guidelines for DOE Long Term Civilian Research and Development, prepared by the Demand Subpanel of the U.S. Department of Energy (DOE) Energy Research Advisory Board (ERAB) (1). The next sections examine each of the above points in more detail.

## 1. INCREASED ENERGY EFFICIENCY IS AN IMPORTANT NATIONAL GOAL.

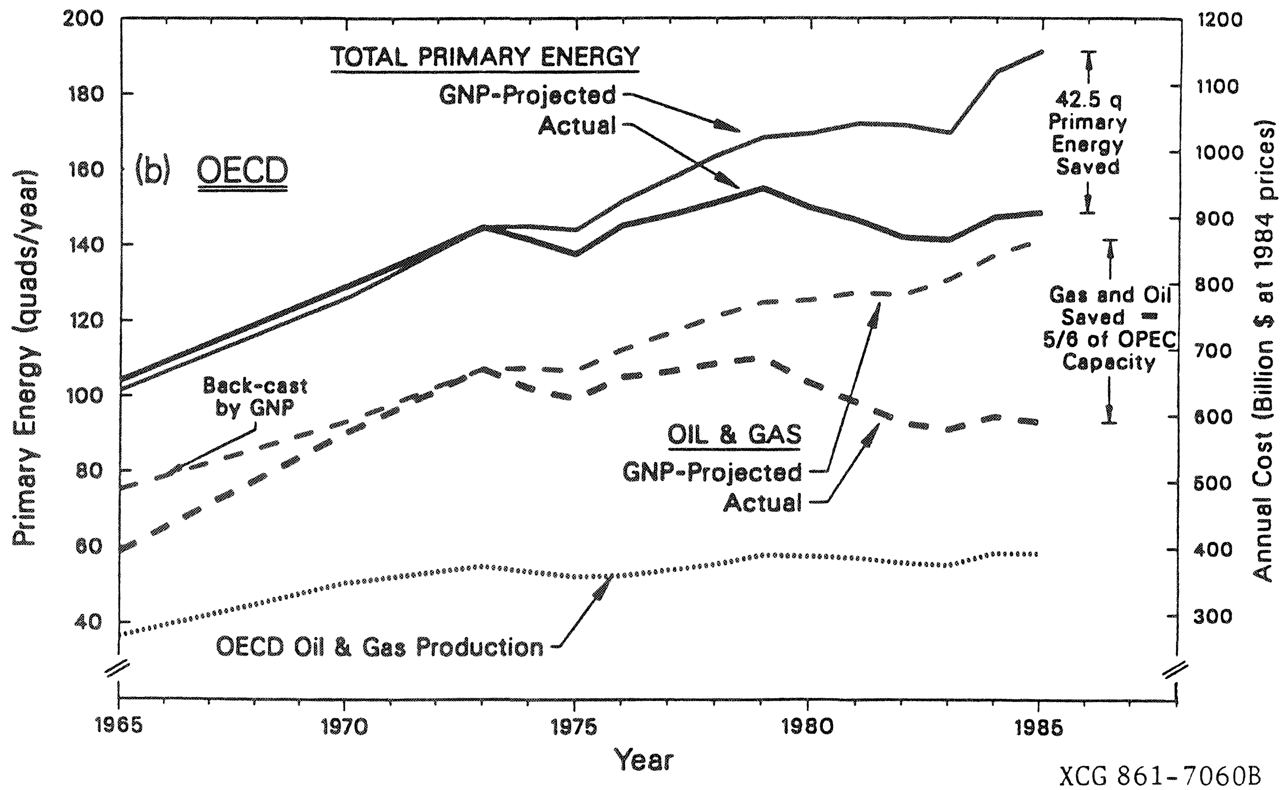
During the past decade Americans recognized the need to enhance national productivity so that U.S. goods and services can compete in the world market. Both the current and previous administrations and the congressional leadership of both parties have recognized that energy efficiency contributes greatly to enhanced productivity, and all have emphasized energy efficiency as a cornerstone of our national energy policy.

Enormous progress in energy efficiency has been achieved during the past decade, although opportunities are still almost limitless. Figure 1a provides a broad perspective. If energy use per unit of GNP were the same in 1985 as it was in 1973, the United States would be spending 30% more for energy--an extra $130 billion per year.

Had we not made these substantial gains in energy productivity, our present energy situation would look radically different. Our trade deficit problems would be even more severe, and it is likely that oil prices would be higher, since extra U.S. oil demand would maintain the pressure on




XCG 861-7060C




XCG 861-7060B

Figures 1a and 1b.

**U.S. AND OECD ENERGY USE: ACTUAL AND PROJECTED BY GNP.**

Projected energy calculated on a GNP basis in constant dollars, with both forecast and "back-cast" values from 1973. Note that the GNP back-cast generally follows the actual consumption curve before OPEC. The "primary energy" on the left-hand scales includes fuel burned at the power plant, in units of "quads" [quadrillion ($10^{15}$) Btu]. The oil and gas savings were converted from quads to fractions of OPEC capacity using an estimated 1986 total OPEC production capacity of 29 Million barrels per day (58 quads). For the right-hand scales, quads were converted to 1985 dollars using the 1984 US cost of energy (about $440 billion for 73 quads).

The lower figure shows comparable data for the entire Organization for Economic Cooperation and Development (OECD). The OECD includes all of North America, Western Europe, Japan, and Australasia, and consumes about twice as much total resource energy as the US alone. Oil and gas savings for the OECD in 1985 were five-sixths of total OPEC capacity.

world supply. Our increased reliance on Middle Eastern oil supplies would make our economy far more vulnerable to oil supply disruptions. The economy would continue to suffer from high prices of energy-intensive goods and services. Finally, the public would be demanding solutions to all of these problems in an atmosphere of even more severe budget imbalance.

Since energy demand growth has been reduced, the present U.S. energy situation is manageable, at least for the near future. Clearly, market forces have played a major role: many energy-intensive industries have moved offshore, slower economic growth has helped dampen energy demand, and higher energy prices have discouraged many wasteful practices by industry and consumers. But a substantial contribution, according to DOE-sponsored studies (2), has also come from technical improvements in the energy efficiency of homes, automobiles, and factories—partly in response to increased energy prices but also reinforced by new technologies, many of which were stimulated by government policies and programs.

The good news is that we do not face an energy crisis today. The bad news is that, with a short-term energy abundance, we run the risk of not anticipating that future energy supplies are likely to be much more costly and not having made our economy resilient to higher priced energy. How effectively will we use the "breathing room" we have earned? And, in the meantime, how long will we continue to build energy-inefficient buildings, factories, and equipment that will continue to guzzle energy long after prices have rebounded?

## 2. LARGE INCREASES IN ENERGY EFFICIENCY CAN STILL BE ACHIEVED.

The slower growth of energy demand since 1973 (Figure 1a) might suggest that most of the waste has been squeezed out of the U.S. economy. This is not the case. To date, much of the reduction in demand growth has resulted from belt-tightening and changes in wasteful behavior patterns. Only some of the savings have come from investments in improved, energy-efficient technology.

Numerous studies suggest that, in addition to the gains already made, the U.S. could reduce its present annual energy bill from $400 billion to $270 billion or less, by adopting only those efficiency measures that are now available and economically justified (3-7,10-12). Most of the U.S. stock of energy-using equipment and buildings was put in place when energy prices were low, and stock turnover is slow in many sectors, even where cost effective investments in more efficient stock can be made. So it is not surprising that much of the existing physical plant wastes energy.

It is important to note that opportunities for cost-effective energy savings are not affected much by the recent decline in world oil prices.[1] This is especially true for the buildings sector, which is increasingly electricity-intensive (in 1986, U.S. buildings consumed $107 billion worth of electricity but only $54 billion worth of oil and gas).[2]

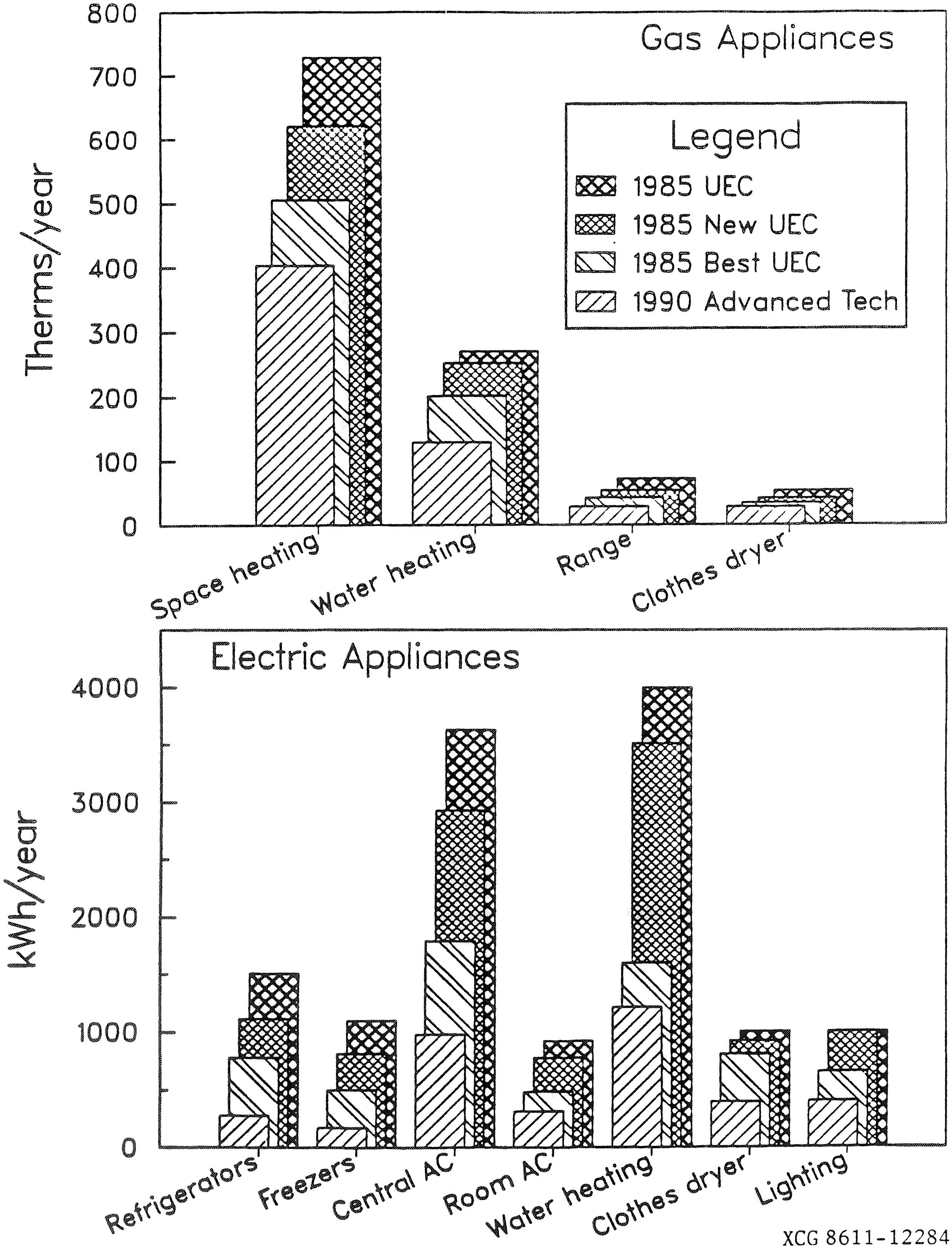
There are still important gains to be made in the energy efficiency of buildings and equipment, but in the future, energy conservation R&D for the buildings sector will increasingly emphasize more efficient use of electricity, including the shifting of loads from peak to off-peak periods. As discussed above, the economic value of these electricity conservation and load-shaping measures will not be affected significantly by oil price changes.

The U.S. still uses as much as 75% more energy per unit of GNP than some of our major industrialized trading partners and competitors. Japan and France, for example, each spend about 6-7% of their gross national product on energy, compared with 11.2% for the United States (7). While not a perfect indicator, this suggests that we are underachieving in making cost-effective energy savings investments. A key issue for the 1990s is whether capital investment in new energy-related facilities and equipment is as cost effective as it could be, in light of current and anticipated energy prices and technology. The short answer is no; on average, today's new capital investments are still far from optimal. A typical new building, which will be in use for the next 50-75 years, still requires almost twice as much energy as one designed and equipped to minimize the total costs of energy, construction, and operation (8).

Energy efficiency of the average new household appliance is also well below that of the best unit available—and even farther below the level of performance that is technically achievable and economic. Figures 2a and 2b shows these relationships for energy use in 1985 for (a) the average gas and electric appliance in all U.S. households, (b) the average new appliance purchased, (c) the most efficient unit available on the market, and (d) an estimate of the best unit that could be made available to consumers in the mid-1990s (9). The figures show that, in many cases, today's best product

[1] Overall conclusions from the studies cited would not change much if they were updated to 1986 conditions. Oil prices would be lower in the near-term, but gas and electricity price assumptions in the studies are still valid. Also, several energy-saving technologies not previously considered are now commercially available.

[2] Nationally, retail electricity prices are quite insensitive to changes in the cost of oil (or natural gas). Oil now represents, on average, less than 3% of the total retail price of electricity, or about 2/10 of a cent per kilowatt-hour. Thus, even if the *average* oil price paid by electric utilities—not just the well published spotmarket price—were cut in half, there would be almost no noticeable effect on the average price of electricity paid by U.S. consumers.




*Figures 2a and 2b. Unit energy consumption of gas and electric household appliances in the U.S. Each set of bars compares energy use by the average model in the 1985 stock, the average new unit and best new unit sold in 1985, and the best technology expected to be available in the 1990s.*

is already 30-40% more efficient than the average new unit purchased. Within a few years, industry leaders could be marketing household appliances that reduce energy use by another 40-50%.

For an individual appliance the energy savings may be modest, but the aggregate numbers are impressive. One year of electric appliance sales represents the amount of energy produced by six large, 1000-MW baseload power plants. This would drop to two power plants if all new models were as efficient as the best projected 1990s technology shown in Figure 2b.

A similar story can be told for energy-using capital equipment in industry; typical energy consumption of new stock could often be reduced dramatically by cost-effective investments (10). Similarly, the fleet-average efficiency of new automobiles could be raised from 26.5 miles per gallon (mpg) to about 40 mpg, reducing fuel use by 34%, at a cost of under $1/gallon of gasoline saved (11, 12). France is developing a 3 liter/100 km (77 mpg) car. Volvo has developed the LCP-2000, which road tests at 63/81 city/highway mpg, easily passes U.S. crash tests, and passes California emissions tests. Toyota's goal for a more compact car is 89/110 mpg. Fiat, Peugeot, Renault, and Volkswagen are also aiming at about 3 liter/100 km (77 mpg) city/highway average.

In summary, the best buildings, appliances, and cars now coming into production are already 30%-40% more efficient than today's average stock, but the gradual introduction of this technologies will not get the U.S. energy/GNP ratio down to the level of Japan's or France's. To achieve that goal during the next 20 years will require pressing forward with technologies now on the drawing board—in other words, maintaining a strong national R&D program targeted to industry's needs. Experience during the past decade has shown that energy conservation R&D will provide excellent value when we compare the cost of research to the value of the resultant energy savings. Also, conducting such R&D now will provide the technology base for a more robust response to any future price escalation or energy supply shortfall. This R&D can begin to embody new scientific breakthroughs in such basic areas as material sciences, bioengineering, and information sciences, and it provides a way to use American intellect to turn back the pressures from foreign manufacturers.

In the next sections, we discuss the past successes and future potential of the federal program.

## 3. THE FEDERAL ENERGY CONSERVATION R&D PROGRAM HAS ACHIEVED DRAMATIC SUCCESSES AND HOLDS THE PROMISE OF CONTINUED SUCCESS.

In Part B, we discuss the case histories of seven energy-efficient developments in lighting, windows, and building equipment. The results are summarized in Table 1.

Table 1 quantifies the dramatic returns on investment generated by DOE-sponsored R&D in the buildings sector. Each of the technologies listed there is yielding large payoffs as it achieves market penetration.

Three had already demonstrated significant commercial success by 1985 (solid-state ballasts for fluorescent lights, low-emissivity window films, and high-efficiency refrigerator compressors). The total government cost of these three projects is only $6 million, thanks to DOE cost-sharing with private industry, and the projects have already produced annual net savings[3] far greater than the total federal R&D investment. In other words, a one-time federal investment of $6 million has already generated an annual return of $25 million—or more than 400% per year.

The near-term benefits are small, however, compared with the eventual impact of full market saturation by these technologies. Taken together, the projects in Table 1 will ultimately save U.S. consumers more than $16 billion per year. Even if we assume that these technologies would have eventually been developed without federal R&D support, the federal government can take credit for accelerating their commercialization by several years, yielding savings of $63 billion. This still represents an extraordinary 4000-to-1 return to the taxpayer on an initial investment of only $17 million.

The technologies listed in Table 1 and other DOE advances in energy efficiency enable architects and engineers to design buildings that are substantially more energy efficient than existing buildings. Building designers will also soon be able to take advantage of new DOE-developed energy standards for federal buildings and energy design guidelines for privately-owned buildings. These standards and guidelines are expected to have enormous impact on building energy consumption because they were developed with the collaboration of the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) and the Illuminating Engineering Society (IES), whose standards are the basis for energy requirements in more than 40 state building codes. DOE has also developed many useful building design tools, including a design handbook for small office buildings that has been very well received by the design community.

[3] Net savings = annual energy savings minus the increase in (annualized) capital cost to buy the more efficient products.

TABLE 1.
Lead-times and Net Savings for Successful DOE-Sponsored Buildings Energy R&D Projects

| | Solid State Ballasts | Low-E Window Films | Residential Absorption Heat Pump | Advanced Electric Heat Pump | High Efficiency Refrigerator Compressor | High Efficiency Refrigerator -Freezer | Heat Pump Water Heater |
|---|---|---|---|---|---|---|---|
| 1. DOE Project Duration | 1976-1980 | 1976-1990[D] | 1978-1988 | 1977-1986 | 1977-1981 | 1978-1983 | 1977-1982 |
| 2. Est. 50% Penetration of Sales | 1995 | 2000 | 2001 | 1998 | 1990 | 1996 | 2000 |
| 3. Years by which DOE advanced commercialization | 5 yrs. | 5 yrs. | 5 yrs. | 2 yrs. | 2 yrs. | 2 yrs. | 2 yrs. |
| 4. Cost of Conserved Energy, (CCE) | 2¢/kWh | $2/MBtu | $2.50/MBtu | $2.75/MBtu | 1¢/kWh | 3¢/kWh | 5¢/kWh |
| 5. Cost of DOE Project | $3M | $2M | $6.8M | $2M | $1M | $0.8M | $0.7M |
| 6. Net Annual Savings in 1985 | $11M | $14M | $0M | $0M | $0.4M | $0.2M | $0.3M |
| 7. Net Annual Savings at Saturation (i.e. 10-15 after 50% penetration) | $5,000M | $3,000M | $2,400M | $2,500M | $1,100M | $850M | $1,800M |
| 8. Cumulative Net Savings (Line 7 x line 3) | $25,000M | $13,000M | $12,000M | $5,000M | $2,200M | $1,700M | $3,600M |
| 9. DOE Project ROI (Return on Investment, =Line 8 ÷ line 5) | 8,000: 1 | 7,000 : 1 | 1,500 : 1 | 2,500 : 1 | 2,000 : 1 | 2,000 : 1 | 5,300 : 1 |

*Notes:*

A. All dollar savings in energy costs are net of increased costs for purchase of the improved equipment (ballast, window, etc.).

B. Line 4. Cost of Conserved Energy, CCE. We use a real discount rate d = 7%, and the useful life of the product: e.g. - 10 years for ballasts, 20 years for windows. The CCE of low-E films, now still a novelty, is currently $4/MBtu, but as the market matures, we estimate that the CCE will drop to $2/MBtu.

C. Line 7. Net Annual Savings at Saturation are in 1985$, uncorrected for: growth in the building stock, changes in real energy costs, or discounted future values. We decided not to account explicitly for these three factors, since all three are uncertain and their combined impact probably small, as shown by the following calculation. To translate savings in 2000 or 2010 to 1985 terms, one multiplies by: exp [(g + e - d)T], with the following annual rates:

g = growth rate of building sector (3%)
e = real price escalation for electricity or fuel (1-2%)
d = real discount rate (4-7%)

} g + e - d = (-3 to +1%)

T = years between 1985 and the est. saturation date, 20 - 25 years.

D. As indicated on line 6, 70m sq.ft. of first generation soft-coat were already installed in 1985, but this soft-coat can be used only between sealed double glazing. Current R&D aims to increase the durability and applicability of sputtered coatings and to produce additional engineering data to better utilize the coatings in sunbelt climates and in commercial buildings.

Table 1 illustrates another important point: the long lead-times involved in research, development, and commercial adoption of a new technology. DOE research on solid-state electronic ballasts, for example, began in 1976 and lasted until 1980, but the ballasts probably will not capture 50% of new ballast sales until the mid-1990s. Since installed ballasts last for 10-15 years, it will take at least another decade before the older core-coil ballasts disappear.

Additional examples of high-impact R&D projects outside the buildings sector are provided by DOE in its 1986 Conservation Multi-year plan. Table 2, from the plan, lists 15 industrial projects that will save $12 billion in 2010, a 400 to 1 payback for federal investment.

Energy efficiency R&D, as these examples make clear, is far from an academic exercise. The total federal investment in energy conservation R&D, averaging less than $200 million per year, has already paid off dramatically in bottom-line economics and has planted the seeds for future energy savings.

These statements should not be misunderstood to suggest that all government energy conservation research projects are successful. Many projects have succeeded, as documented in Tables 1-2 and in the case studies, but others have failed to work as hoped, or have been slow in achieving commercial acceptance. This pattern is inherent in research programs. In fact, without risky projects that industry is unlikely to pursue by itself, there would be less justification for federal involvement. Nonetheless, federal researchers must remain vigilant in weeding out once-promising research concepts that are not meeting technical or economic expectations, and they must make efforts to ensure their research is relevant to the nation's industry.

Perhaps paradoxically, the failures in energy conservation R&D illustrate an important advantage of research on end-use energy efficiency: these R&D efforts are *diversified*, so that failures can be offset by successes. In contrast, when government or private resources are concentrated on a few large-scale projects—as with some energy supply technologies (e.g., the breeder reactor) —any setback is very costly, in both lost dollars and lost time.

**Table 2. Selected completed industrial research projects**

| Technology (year commercially available) | DOE project cost ($ millions) | Current savings (1985) ($10^{12}$Btu/yr) | Estimated savings year 2010 ($10^{12}$Btu/yr)[b] | Estimated savings year 2010 (million 1986$)[a] |
|---|---|---|---|---|
| Coal fired steam turbine-cogeneration (1983) | 1.4 | — | 344 | 1720 |
| Slow speed diesel-cogeneration (1983) | 11.0 | — | 516 | 2580 |
| Catalytic reactor (1982) | 1.5 | — | 265 | 1325 |
| Computer controlled oven (1981) | 0.5 | — | 228 | 1140 |
| Controlled speed accessory drive (1981) | 0.8 | — | 50 | 813[c] |
| Cupola stack air injection (1981) | 0.9 | — | 25 | 125 |
| Dye bath reuse (1979) | 0.2 | — | 19 | 95 |
| Foam finishing (1980) | 1.1 | — | 52 | 260 |
| High efficiency welding unit | 0.4 | — | 42 | 210 |
| Nitrogen-methanol carburization (1981) | 0.4 | — | 10 | 50 |
| ORC bottoming unit (1981) | 3.0 | — | 225 | 1125 |
| Plating waste concentrator (1981) | 0.4 | — | 22 | 110 |
| Metallic recuperators (1979) | 1.5 | — | 178 | 890 |
| Ceramic recuperators (1979) | 2.6 | — | 247 | 1235 |
| Slot forge furnace (1978) | 2.4 | — | 20 | 100 |
| Total, in $ millions | 28 | — | 2250 | 12,000 |
| Payback | | | | 400:1 |

a Resource energy converted to dollars = $\$5000/10^6$ Btu, i.e., $5 billion per quad.

b Estimates of national energy savings projected by 2010, given the market penetration performance history of these or similar technologies.

c Based on $16.26 per million Btu for gasoline.

Source: 1986 DOE Conservation Multi-year Plan, Table 2-2. See (21).

## 4. ADVANCES IN ENERGY-EFFICIENT TECHNOLOGIES ARE NEEDED TO ENSURE A STRONG COMPETITIVE POSITION FOR U.S. INDUSTRY IN THE WORLD MARKET.

The previous section identified a number of advanced energy-efficiency technologies with strong commercial potential. But who will be the technological leaders in these growth sectors, U.S. firms or their overseas competitors? The answer depends, in part, on a continued strong federal role in advanced technology R&D.

Three contrasting examples from the lighting industry illustrate this point. The first involves electronic ballasts for fluorescent lights, described in Part B. DOE-supported ballast R&D projects reduced technical risks, shared information with industry, and helped U.S. firms bring a new product to market, maintaining their strong domestic position.

A similar joint DOE-industry research program on compact, screw-in fluorescent lamps was halted in 1981—while still in its formative stage—by federal funding cuts. The Japanese and Europeans continued work on these lamps, however, and by 1985 a number of Japanese and European firms introduced compact, screw-in fluorescent high-efficiency lamps. General Electric Co. is now selling a screw-in fluorescent lamp made by a Japanese manufacturer.

The third case still hangs in the balance. It involves lighting controls, a market with very high growth potential over the next few years. Recent DOE-funded research has again provided much of the technical foundation for U.S. companies to establish a position of market leadership. With continued federal support, DOE and industry could take advantage of this multi-billion dollar market.

Another high-technology product line the U.S. is losing rapidly to foreign competitors is efficient electric motors and controls. U.S. industrial, commercial, and residential consumers pay about $80 billion per year for power to run electric motors. Recent advances in magnetic materials and power electronics are greatly improving the efficiency of these motors and motor-driven systems and reducing costs to consumers. Permanent-magnet motors, for example, can have 20% lower losses than the best induction motors, run cooler, are smaller and lighter, and are more precisely controlled. Current applications include machine tools, robotics, computer peripherals, and home appliances.

A recent study (13) points out that:

> U.S. competitiveness in this rapidly growing market for new motor technologies is of concern, however. As pointed out by the National Materials Advisory Board, 'The fundamental work leading to the REPMs [rare-earth permanent magnets, such as SmCo]

> was done largely in the United States... but after government support ceased, materials R&D in the U.S. magnets industry deteriorated. Practically all recent PM materials have been developed to commercial maturity in Japan.'
>
> Thus, the NMAB concludes that 'despite the critical importance of magnetic materials, the U.S. is rapidly losing its competitive position,' in a market that is expected to reach $2 billion annually next year.

The fast growing market in power electronics (electronic devices that control power consuming equipment) is also facing intense foreign competition. For example, electronic adjustable speed drives (ASDs), which control the speed of electric motors subjected to varying loads and reduce electricity use by 20%-30%, use basic components that were first developed by American companies. Nonetheless, foreign control of the U.S. market for ASDs has grown from 15% in 1980 to more than 40% in 1985. Foreign companies have not only taken over the lead in production of ASDs, they have taken the lead in innovation and product improvement.

Ralph Ferraro of the Electric Power Research Institute estimates that the U.S. manufacturers' share of the domestic power electronics market will erode from its present level of 50% to about 25% within five years. According to the Federation of Materials Societies, "if the current trend continues, it can be anticipated that the U.S. will be a minor force in the world market in electronic materials and systems by the 1990s" (14).

A final example is in the area of housing technology, an industry that is traditionally seen in the United States as fragmented and slow to accept technical innovation. Compare our situation to that in Sweden, where the government supports an ambitious R&D program in all aspects of basic and applied building technology (15). Sweden's total funding of its program is similar to that in the United States, even though the Swedish market is only about one twentieth the size of ours. Swedish researchers have produced a host of technical innovations that are already used in "superinsulated" houses around the world. Applications of R&D results to an industrialized building sector have made high-quality, energy-efficient homes the norm in Sweden, rather than the exception. Several firms are now exporting their factory-built housing to the United States, and beginning to compete successfully in upscale markets.

These examples show the commercial importance of energy-efficiency technologies. The key question is how to help U.S. industries be more competitive. Part of the answer is basic and applied R&D, where the federal government, as discussed in the next section, is a crucial player.

## 5. THE FEDERAL GOVERNMENT HAS AN ESSENTIAL ROLE IN ENERGY CONSERVATION RESEARCH.

Both private and public sector R&D are investments in the future. Industries and nations that invest too little in R&D, or fail to pursue potentially valuable projects to their logical conclusions, will lose opportunities for competitiveness, innovation, and productivity. Such losses are usually not apparent for some years, as industry lives off past research and dissipates historically developed goodwill, but a lack of high-quality R&D inevitably cripples industries and weakens whole economies.

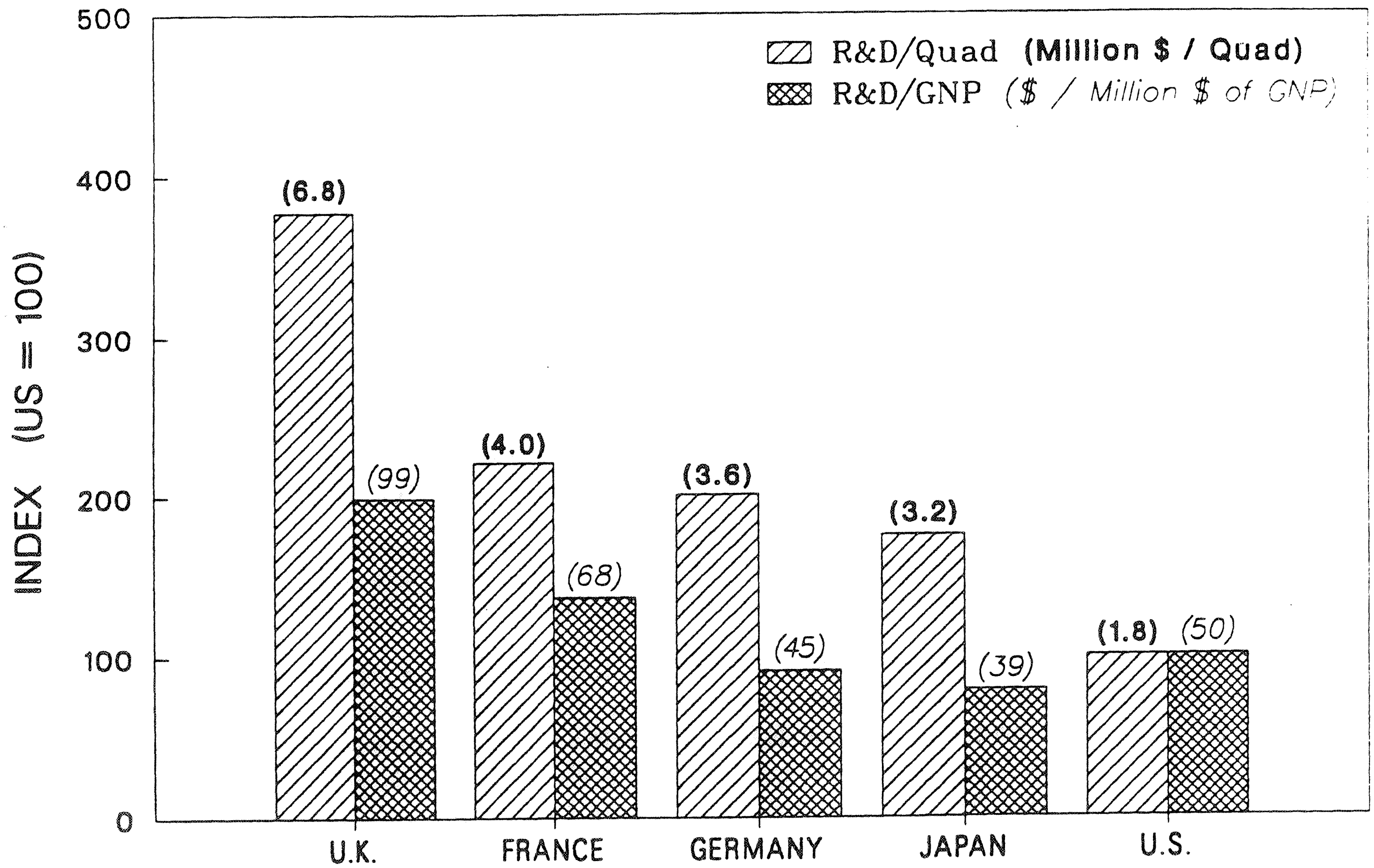
Comparative data shown in Figure 3 demonstrate that other industrialized countries often give much higher priority to government investments in energy-efficiency R&D than does the United States (16). Using one index, conservation R&D spending per quad of energy use (light cross-hatching in the figure), the United States ranks last among the five countries shown. An alternative index, R&D spending as a fraction of GNP (dark cross-hatching), places the United States third—but still well below France and the United Kingdom. If the French government's program for energy conservation R&D were scaled to the United States, it would represent between $260 and $380 million per year (according to whether the scaling factor is GNP or energy consumption) (17). This compares with U.S. conservation R&D expenditures of only $173 million for FY 1986 (including information and technology transfer), a figure that was further cut to $162 million in FY 1987.

There are widely differing views on the appropriate federal role in energy conservation R&D. The following policy statement in the DOE Energy Conservation Multi-year Plan reflects DOE's approach (18):

> The federal role in energy research and development is concentrated in areas where the incentives for and availability of private investment are severely limited or nonexistent.... The success of federal research and development programs in providing options for private investment and commercial development depends on effective technology transfer.

In addition, however, the process of developing usable technologies should involve prospective users in all stages of the R&D process, from formulation to demonstration.

DOE emphasizes federal research and development in those areas where the private sector has too little incentive or too few resources. This policy must be interpreted in light of recent findings on the limited extent of private R&D investments in many sectors of U.S. industry. A recent study of appliance manufacturers and markets worldwide showed that U.S. firms, which have historically been insulated from world competition and have only a limited research infrastructure, spent only 1%-2% of their




XCG 8611-1226

**Fig. 3. Government Spending for Energy Conservation R&D in Five Industrialized Countries.**

The data show that other industrialized countries often give higher priority to energy efficiency R&D than does the U.S. One measure of this is Conservation R&D spending per Quad of energy use (light cross-hatching); the U.S. ranks fifth among the five countries shown. A second index is R&D spending as a fraction of GNP (dark cross-hatching); the U.S. ranks third, still well below levels for France and the U.K.

The values shown at the end of each bar are millions of U.S. dollars spent per quad, and dollars spent per million dollars of GNP, respectively. The left-hand scale shows both measures indexed to the U.S. spending (U.S. = 100); thus, we see that the United Kingdom spends almost four times as much for R&D as the U.S. per quad of energy used.

These data were converted to dollars using average 1980 exchange rates, as published by the International Monetary Fund. Current exchange rates are less favorable to the U.S., and would show the U.S. to rank even lower than above.

1983 sales revenue on all R&D (not just that aimed at energy efficiency), in contrast to an estimated 3%-4% spent by Japanese appliance manufacturers. For comparison, rapidly advancing high-technology industries in the United States typically allocate 4%-7% of revenues to R&D (19).

Other reviews of manufacturing R&D have found that private firms often have limited incentive or resources to undertake their own research because of near-term pressures on market share and profitability, high up-front research costs, risks of failure, and uncertain competitive advantage from a new advance, which might be rapidly adapted or copied by other firms. Nor is it apparent that the modest federal tax incentives provided for industrial R&D have had any significant impact (20).

With regard to the building industry, the recent ERAB Demand Panel report states that:

> Many small design firms, building companies, and component manufacturers comprise the building industry. Most private firms will undertake basic R&D activities if there are substantial and immediate monetary gains for the firm, and this is seldom possible in a fragmented industry of small firms. As a result, too little R&D is performed and [it] must be supplemented by the government if it is to be accomplished on any substantial scale.

In FY 1987 DOE sought to enlarge its joint programs with private industry both to sustain the scope of its research effort and to enhance the probability that industry will use the results. Collaborative, cost-shared research is a sound idea, and in many cases is already a feature of successful DOE-sponsored energy-efficiency R&D. But unfortunately, the private sector tends to reduce its own participation in step with any withdrawal of federal R&D support.

Discussions with industry R&D leaders, including the two largest industry organizations doing research on energy efficiency in buildings (the Electric Power Research Institute and the Gas Research Institute), reveal no prospect of private industry funds that might substantially replace federal funding for efficient use of energy. Even if such private funding could be generated, it would take many years to change industry priorities and to organize new collaborations between the federal government and individual firms or industry research establishments.

One other essential element of DOE-funded R&D should be underscored: the work on fundamental, "technology base" activities, rather than specific products or devices. The benefits of this research are more difficult to quantify than the product-oriented R&D discussed above, but they are no less crucial. For example, basic research on phosphors such as those used in fluorescent lamps could lead to a doubling in the efficacy of those phosphors. Industry depends on such government-sponsored research to provide a basis from which it can build innovative, marketable new products. The relatively long-term nature of such research, the highly specialized expertise required, and the lack of directly marketable products resulting from such research limit the ability of most industries to pursue it in the absence of a leading federal role.

Finally, the DOE Multi-year Plan points to the benefits of a federal technology transfer program. Successful R&D needs to get into the market to have an impact on more efficient use of energy, and technology transfer must be intrinsic to the research effort and be supported adequately and explicitly at a high level. Successful research is meaningless unless it is used.

To summarize, DOE's stated policies on the appropriate federal role in energy efficiency R&D is not at issue. The issue is how much government support is appropriate, which depends, in turn, on an assessment of the magnitude of the problem and/or opportunities involved in the research and the degree to which government activities can make a cost-effective contribution. The opportunity in this case is large. Energy conservation is an important way to address competitive pressures from overseas industries, and by not conserving more, we are risking another round of over-dependence on foreign oil. Federal support of energy conservation R&D is key to addressing these issues over the long term; private industry cannot do it alone.

## 6. FEDERAL ENERGY CONSERVATION R&D CONTRIBUTES TO THE UNDERLYING POLICY OBJECTIVES OF THE GRAMM-RUDMAN-HOLLINGS LEGISLATION BY REDUCING UPWARD PRESSURE ON INTEREST RATES AND FREEING UP CAPITAL FOR MORE PRODUCTIVE INVESTMENTS.

Congress enacted the Gramm-Rudman-Hollings legislation because among other reasons, heavy federal borrowing to finance the federal deficit was competing with private borrowing and thereby was driving up interest rates and reducing available capital. The energy industry is also a heavy borrower of capital. In 1982, it accounted for 40% of total investment in plant and equipment (21).

Figure 4 is from the September 1986 Electrical World magazine, a major publication of the electric utility industry. The figure shows annual investment in electricity supply declining from $50 billion per year in 1979-1983 to a projected low of $17 billion around 1990. This precipitous drop in investment is projected to free over $30 billion per year —nearly 10% of total annual investment in plant and equipment— for other productive uses of capital. Electrical World predicts a subsequent rise in annual investment, to $45 billion by 2000. But with a balanced program

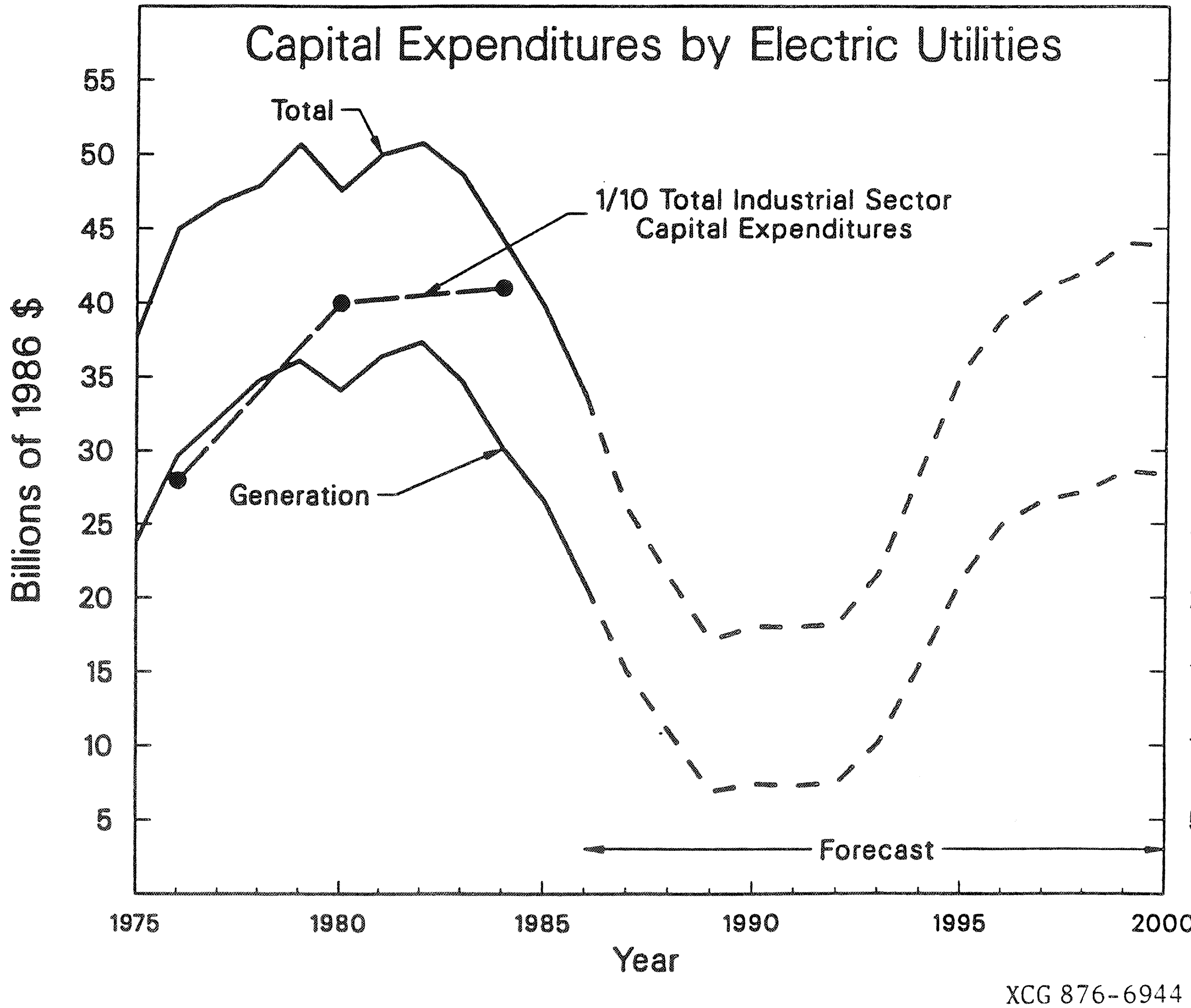



Figure 4. Electrical industry annual investment in plant and equipment, in 1986$. The equivalent investment by all of industry is about $1B per day, so that the electric fraction has dropped from about 15% ($50B) to a minimum that will be about 5% ($17B). The utility investments do not include cogeneration, which is running at about $2B/year. Source: Electrical World, McGraw-Hill, Inc., Sept. 1986. Figures for total industry investment are from *1986 Statistical Abstract of the United States*, 106th Edition, Table 901, p. 529, using GNP implicit price deflators to convert to 1986 dollars.

of resource planning, and equal treatment of investments in supply and efficiency, this projected rise can be deferred and attenuated.

In short, *increased energy efficiency can make a significant contribution to the objective of increased capital availability and lower interest rates.* It makes no sense to disproportionately slash federal funds for energy conservation R&D in the name of the policy goals that conservation R&D helps achieve.

## 7. ENERGY EFFICIENCY HAS IMPROVED NATIONAL SECURITY BY DRAMATICALLY REDUCING OIL IMPORTS. ENERGY CONSERVATION R&D CAN FURTHER REDUCE OIL IMPORTS.

A recent report by the U.S. Department of Energy to the President estimates that U.S. oil imports are expected to increase from their 1985 level of 5 million barrels per day (mbd) to between 8 and 10 mbd by 1995, an increase in oil import dependency from one third to about one half. This projection is based on a combination of declining domestic oil production and increasing domestic demand for oil. Almost all of the increased imports are likely to come from OPEC countries, which have about 95% of the world's excess production capacity. Such a major shift toward dependence on OPEC oil could create enormous economic and security problems for the U.S. (22).

If not for recent improvements in U.S. energy efficiency, the coming oil problem would be much worse and probably would have materialized years ago. Improvements made between 1972 and 1984 in the efficiency of the U.S. cars and light trucks are by themselves responsible for reducing U.S. oil consumption by 1.5 mbd (23). This rate of saving is equivalent to the rate of oil production for the entire state of Alaska.

As was shown in Figure 1a, if the U.S. economy still consumed oil and gas at the rate it did in 1973 (per dollar of GNP), we would be consuming an additional 13 mbd (oil equivalent) of oil and gas. Thus, we are now saving, each year, fully half of OPEC's oil production capacity of 29 mbd.[4] Oil and gas savings, compared to 1973, are equivalent to the output of OPEC at its 1985 rate of production of 18 mbd.

Although much of the reduction in U.S. oil use was brought on by regulation (fuel economy standards), switching to less expensive fuel (such as coal) and technical improvements spurred by rising oil prices, federally-supported R&D has made important contributions to improving the efficiency of oil use. For example, the flame-retention head oil burner was

[4] The efficiency of oil and gas use is aggregrated, as is done in the Energy Information Administration's Monthly Energy Review, because to a significant degree, oil and gas are substitutable fuels.

developed at Brookhaven National Laboratory with DOE support. This burner can be installed in an existing residential oil furnace. It is about 85% efficient, compared to 70% efficient conventional burners, and saves about 175 gallons of oil per year in a typical oil-heated house, of which there are about 15 million in the U.S. If flame retention head burners were installed in all these homes, oil savings would be equivalent to removing 6 to 7 million new cars from the road. Use of flame retention burners is now growing rapidly.

Energy efficiency improvements in the transportation sector are especially important for improving national security because this sector accounts for 62% of U.S. oil use, a percentage that has been growing steadily over the last decade. In recognition of the importance of reducing transportation sector oil use, DOE supports a number of long-range research programs to develop new, efficient power systems for cars and trucks. Extensive research has been performed on gas turbine engines (which are expected to be 30% more efficient than conventional engines and have multi-fuel capability), sterling engines (which use a heat source external to the engine and have multi-fuel capability), electric vehicles, and adiabatic diesels (high-temperature, low-heat-rejection, high-efficiency diesel engines). It is projected that an adiabatic diesel installed in a Ford Tempo with a continuously variable transmission (CVT) would boost the car's mileage from 38 mpg to 80 mpg. The adiabatic diesel is responsible for about 85% of this potential improvement.

The development of high-temperature, high-strength, corrosion-resistant ceramic materials has been central to DOE's research in improving transportation energy efficiency. In 1987 GM will introduce a special edition of the Buick Regal with a ceramic turbocharger supplied by the Garret Corporation, which has worked closely with DOE on ceramic turbine development. When fully absorbed by the market, advanced turbochargers with ceramics rotors are expected to reduce U.S. motor fuel consumption by 0.6 to 1.0 billion gallons per year (24). Additional energy and economic savings are expected as other ceramic engine components that incorporate DOE-supported research are commercialized. Argonne National Laboratory estimates that U.S. GNP will be increased $279 billion (1981 $) during the first 20 years of market penetration of ceramic components in heat engines (25).

Reducing oil consumption in the transportation sector is one of the most important issues in our country's economic future. In the absence of major changes in how we use oil for transportation, the U.S. could easily slip back to the dangerous position we were in during the 1970s. A major effort is needed to reduce our dependency on important oil, and improving the energy efficiency of the transportation sector should be a large part of that effort.

## 8. FEDERAL ENERGY CONSERVATION R&D HAS HELPED IMPROVE THE EFFECTIVENESS OF LOW-INCOME WEATHERIZATION PROGRAMS.

The federal government has spent in excess of 2 billion weatherizing homes occupied by low-income families. Most of these homes were badly in need of repair and general maintenance and had old, inefficient heating equipment. But many federally supported weatherization programs, particularly in their early years of operation, were unable to cost-effectively reduce energy consumption in these homes.

Experience, research, and program evaluation have enabled weatherization personnel to substantially improve program effectiveness; much of this increase in understanding how best to reduce energy consumption in low-income buildings has come from the Department of Energy's energy conservation R&D program. New energy auditing procedures and energy-saving technologies, a better program evaluation method, reliable information on the effectiveness of weatherization measures, and an overall better understanding of how houses consume energy are just some of the products of DOE's conservation R&D that have improved the Weatherization Assistance Program (WAP).

Development of a reliable methodology to estimate energy savings from conservation measures is one of the most valuable research contributions. Dubbed PRISM (the Princeton Scorekeeping Method), this DOE-supported method has enabled managers overseeing weatherization programs to rigorously evaluate the effectiveness of their programs, identify weaknesses, and make program improvements. PRISM is increasingly being used to evaluate weatherization programs. For example, it was used in 1984 to evaluate Wisconsin's weatherization program. The highly regarded program was found to be reducing energy consumption only about 6-10% per home, a figure which was much lower than expected. As a consequence of the evaluation, the program underwent a number of changes to improve its effectiveness. An evaluation of the newly restructured program has not been completed yet (26).

"House Doctoring," a substantially different approach to improving the energy efficiency of homes, was another DOE-supported R&D project that is useful to the WAP. Conventional house weatherization emphasizes improvements to building envelopes, such as insulation, weatherstripping, caulking, and storm doors or windows. House Doctoring uses trained technicians armed with analytical instruments and weatherization materials. The technicians use their instruments to pinpoint sources of heat loss (particularly convective heat loss and thermal bypasses) and equipment inefficiencies. Simple-to-correct deficiencies are remedied immediately. Major weatherization measures, such as insulating large areas, can be completed after a House Doctor visit. In a study conducted during 1982-83, the House Doctor approach was compared to standard weatherization procedures in low-income homes in New York City. The study, which used PRISM, concluded that while the conventional weatherization procedure yielded savings averaging 2.5% per house, the House Doctor approach with follow-up weatherization retrofits (as recommended by the house doctors) yielded average per home savings of 20% (27).

A recent study completed with support from DOE's energy conservation R&D program confirmed that improvements to heating equipment efficiency can substantially increase the cost-effectiveness and energy savings of low-income weatherization programs. The Wisconsin study found that a weatherization protocol including equipment efficiency improvements produced twice the energy savings of a conventional weatherization protocol (which emphasizes improvements to the thermal envelopes of houses) at 25% lower cost (28).

The Office of Buildings and Community Systems (OBCS) in DOE's energy conservation R&D program has initiated a project to familiarize state energy offices and and weatherization agencies with research results that can improve the effectiveness of their programs. By staying informed on the most current research and adopting the most promising new procedures and technologies, weatherization program managers can steadily improve the effectiveness of their programs.

## 9. CONCLUSION

The proposed reductions in federal energy conservation R&D carry a double penalty for the U.S. economy and all consumers:

1. Given the lead-times of 10 years or more for development and commercialization of advanced energy-saving technologies, we cannot afford to abandon or defer R&D investments needed now for long-term economic vitality.
2. Many R&D projects also have near-term payoffs. Even with a (temporary) softening of world oil prices, we can continue to save billions of dollars each year from the earlier introduction of cost-effective energy-efficient technologies. Reducing the nation's energy bill makes our industries more productive, slows inflation, reduces our trade deficit, and gives each consumer more money to spend in job-creating sectors of the economy.

DOE's current R&D program contains numerous projects with the same potential for success as those already completed. These projects and their rationale are described in several DOE reports, including the Multi-year Plan. The data provide convincing evidence of the enormous value, both now and in the long run, of a well-formulated energy conservation research effort.

We recognize that controlling the federal deficit requires strong, even painful, action. However, activities that have demonstrated their success in meeting important national needs—including the objectives of the Gramm-Rudman-Hollings legislation—must be recognized and supported. We must maintain the momentum achieved through federal energy conservation R&D to avoid crippling the nation's prospects for energy and economic security.

# PART B CASE STUDIES

## 1. SUMMARY

We now present case studies of seven R&D successes in building components and equipment. Many other equally impressive success stories could be recited due to conservation research in industry and transportation. By "success," we mean that the improved technology is already in or near commercial production, and will achieve 50% market penetration in 5-15 years. We can then evaluate the annual savings at market saturation, which occurs roughly 30 years after project initiation. These seven examples alone will save U.S. consumers $18 billion per year (scaled back to today's economy). Since federal support advanced these savings by 2-5 years, we estimate the cumulative savings attributable to DOE R&D to be $68 billion.

The payback calculations for these developments do not attempt to estimate any secondary benefits that may derive from the resulting enhanced competitive position of U.S. manufacturers or from increased national energy security.

These cases are summarized in Table 3 and presented in shortened form in Table 1 (Part A). A typical feature of these seven cases is their low cost of conserved energy, i.e. the cost of providing the desired service by improving efficiency instead of purchasing electricity or gas. The cost of conserved electricity ranges from 1 to 3 cents/kWh vs about 10 cents/kWh for new power today; for natural gas the cost of conserved energy ranges from $2-3 per million Btu (MBtu) vs $6/MBtu for retail gas today. Thus, conservation has been 2-10 times cheaper than new energy supplies.

An important common element of these seven cases is the early involvement of private firms, generally through subcontracting. In most instances, private firms did most of the development. Often small (sometimes very small) businesses played key roles. They did the early development, and when the innovation demonstrated commercial viability, larger firms became involved through buyout or partnership. Government R&D efforts were the catalyst in this public/private sector partnership, supplying the financial resources, technical support, and independent evaluation through the national laboratories. This support was sustained long enough for the product to successfully enter the market.

**Table 3. Summary of Building Conservation Case Studies.**

| | Solid state ballast[a] | Low-E window films[b] | Residential absorption heat pump | Advanced electric heat pump | High efficiency refrigerator compressor | High efficiency refrigerator/ freezer | Heat pump water heater |
|---|---|---|---|---|---|---|---|
| 1. Annual energy savings (Btu/unit or kWh/unit) | 100 (133)[a] kWh | 50,000 Btu/$ft^2$ | $26 \times 10^6$ Btu | $48 \times 10^6$ Btu | 162 kWh | 280 kWh | 2200 kWh |
| 2. Gross savings/unit (1985 $/yr) | 7.5 (10)[a] | 0.30/$ft^2$ | 333 | 404 | 13 | 22 | 176 |
| 3. Life (years) | 10 | 20 | 20 | 15 | 17 | 17 | 12 |
| 4. Cost premium ($) | 12 | 1.0 | 800 | 1300 | 15 | 100 | 700 |
| 5. Annualized capital[c] ($) | 1.70 | 0.10 | 71 | 133 | 1 | 10 | 88 |
| 6. Net savings/unit ($/year) | 5.80 (7.75)[a] | 0.2 | 262 | 271 | 12 | 13 | 88 |
| 7. Simple payback (years) | 2 | 5 | 2.4 | 3.2 | 1.1 | 4.5 | 4 |
| 8. U.S. stock (millions) | 625 | 18,000 $ft^2$ | 17 | 19 | 100 | 100 | 28 |
| 9. Saturation penetration (%) | 95 | 80 | 74 | 67 | 92 | 66 | 75 |
| 10. Saturation units (millions) | 600 | 14,000 $ft^2$ | 13 | 13 | 92 | 66 | 21 |
| 11. Net annual savings at saturation (1985 $, billions)[d] | 3.5 (4.6)[a] | 3 | 2.4 | 2.5 | 1.1 | 0.85 | 1.8 |
| 12. Cost of DOE project ($, millions) | 3 | 2 | 6.8 | 2.0 | 1.0 | 0.8 | 0.7 |
| 13. Commercialization advance (years) | 5 | 5 | 5 | 2 | 2 | 2 | 2 |
| 14. Net project savings ($, billions) | 15 (25)[a] | 13 | 12 | 5 | 2.2 | 1.7 | 3.7 |
| 15. DOE project return on investment | 8000:1 | 7000:1 | 1800:1 | 2500:1 | 2200:1 | 2000:1 | 5300:1 |

[a] The main column of entries describes ballasts which save 25% without feedback dimming control to compensate for daylight and lamp aging. Photocells and dimmers roughly double the surcost and the savings, leaving the cost of conserved energy unchanged. We estimate that 50% of lamps will be undimmed, 50% dimmed, with average savings of 33%. These average predicted values are shown in parentheses.

[b] Unit savings and costs are per square foot of film.

[c] 7% real discount rate, without tax preferences.

[d] Annual savings are uncorrected for growth in building stock. See note C of Table 1.

## 2. LIGHTING

*Energy-Efficient Solid-State Ballasts for Fluorescent Lighting*

In 1976 DOE established a lighting research program at the Lawrence Berkeley Laboratory (LBL) to accelerate the commercialization of energy-efficient lighting technologies. LBL researchers under the direction of Sam Berman soon focused on the potential of solid-state ballasts, which power fluorescent lamps at high frequency, to reduce the energy needed for lighting by 15-30%. Calculations showed that if such high-efficiency ballasts were to saturate the U.S. market, they could save $5 billion per year as a result of reducing energy demand by an amount equal to the output of 10 typical large (1000 MW) power plants.

None of the major ballast manufacturers showed any interest in the program or replied to a 1976 request for proposal (RFP) that LBL issued for cost-sharing subcontractors to develop circuitry for the ballasts. However, about 14 small entrepreneurial firms did apply. This pattern appears in many of the R&D case studies discussed here. Large established firms have shown little interest in the early stages of product development, while small companies jumped at the opportunity to conduct joint R&D with the government. It appears therefore that modest federal funding helped speed valuable research that large firms would not have pursued on their own initiatives and that small firms working alone could not afford. The results of this public-private partnership are impressive, both for the potential energy savings to society and for the business successes they have generated.

In 1977 LBL selected two contractors to develop prototypes. IOTA Engineering submitted a low-cost, nondimmable design, and Stevens Electronics submitted a sophisticated high-performance design that was not only more efficient, but could also dim the fluorescent lamps down to 10% of full light output.

The first prototype delivered to LBL for testing showed that the new high-frequency ballast could increase lighting efficiency 25%, by combining 15% better lamp performance with reduced transformer losses from the ballast itself. The first generation of ballasts was not reliable enough, however, so LBL arranged to have a second generation prototype developed and installed for demonstration and testing at the headquarters of the Pacific Gas & Electric Company (PG&E) in San Francisco. The federal laboratory's involvement in this research lent the credibility needed to get a major demonstration program approved at such a highly visible location.

In 1978, 500 IOTA ballasts were installed on one floor at PG&E, 500 Stevens ballasts on a second, and 500 energy-efficient electromagnetic ballasts on a third. LBL monitoring confirmed that the new ballasts reduced lighting energy consumption by 25% without compromising illumination. However, a considerable number of ballasts failed, owing to design faults not identified in limited laboratory testing.

In 1979, after the design problems were corrected, commercial interest in the ballasts increased. Beatrice Foods, Inc., bought IOTA's concept and patents rights and formed a division, EE Tech, to develop and produce the product. Stevens Electronics sold its exclusive rights to Luminoptics, a company established to manufacture and market the Stevens design.

In 1979, the Veterans Administration Office of Construction proposed to cofund with DOE a demonstration of the advanced dimmable ballast prototype in a medical center in Long Beach, California. LBL placed more than 400 ballasts supplied by Luminoptics in the medical center, measured their energy savings and reliability, and studied their compatibility with personnel and equipment. After this successful demonstration, the Veterans Administration Office of Construction became the first federal agency to specify the use of solid-state ballasts.

Throughout the period when the ballasts were being developed, LBL published its findings and made numerous presentations to the lighting community and general public. Major U.S. ballast manufacturers continued to show little interest, although two foreign companies, O. Y. Helver (Finland) and Toshiba (Japan), began producing solid-state ballasts in 1980. From 1980 to 1984 a dozen small domestic manufacturers struggled to establish a market for solid-state ballasts and to improve the reliability of their products. The relatively conservative lighting industry was slow to adopt these innovative designs, even though foreign firms were already entering the domestic market with energy-efficient lighting products. LBL's program support was reduced during this period, but it continued to publicize the benefits of solid-state ballasts and to test the new products for reliability. LBL also worked with the manufacturers and the Federal Communications Commission to develop voluntary standards to ensure that electromagnetic radiation emitted by the high-frequency ballasts would not interfere with computers, communications devices, and other electronic equipment.

By the end of 1984, one million solid-state ballasts for the F40 (40-watt) fluorescent lamp had been sold in the United States. Though this was a small number in comparison to the total annual demand for 70 million units, the proven credibility of the products, in concert with LBL's R&D support, information dissemination, and technology transfer, had finally brought the solid-state ballast to the brink of commercial success.

In 1984, General Electric and GTE announced lamps designed to be operated with a solid-state ballast. This signified that the major lamp manufacturers had recognized an important new market. In 1985, General Electric announced a solid-state ballast, and Universal Manufacturing announced a low-cost dedicated solid-state ballast. In 1986, Advanced Transformer, the largest U.S. ballast manufacturer, announced plans to market a solid-state ballast for two 40-watt F40 fluorescent lamps. Small companies are still entering the field expecting to obtain a market share for special applications. The market for solid-state ballasts is expected to grow rapidly, and should achieve 50% penetration by 1995 and saturation by the year 2000.

The successful strategy and perseverance of the LBL/DOE program, with the coordinated and cost-shared investment of small companies, has created a new, efficient lighting technology. DOE funding for this program during the past nine years was only $2.7 million, approximately half of which was subcontracted, with subcontractors providing an additional $1 million.

Today, two million solid-state ballasts are in operation in the United States, each saving on the average 25 watts for 4000 hours annually, a total savings of 200 million kWh per year. At a typical energy cost of $0.075/kWh, the annual savings are worth more than $15 million. Within 30 years, the cumulative net savings from the government's participation will total approximately $25 billion. This achievement reflects how an effective DOE strategy to promote technological innovation can succeed even in a restricted environment dominated by a few large corporations with a seemingly captive market. The 1980 foreign import threat appears to have been repulsed.

## FUTURE POSSIBILITIES

The high-frequency solid-state fluorescent ballast is the key technical element allowing more widespread use of dimming controls. Standard core-coil ballasts can dim fluorescent lamps by conditioning their input power (voltage reduction or phase control). Solid-state ballasts dim lamps by low-voltage signals, reducing the cost and increasing the flexibility of the control system. Solid-state ballast control systems independently dim single lamps as well as large banks of lamps. Conventional core-type ballast systems, in contrast, can dim only banks of lamps at greater expense.

Thus, in addition to catering to individual demand preferences, such as scheduling, adjusting the light to match the task, and compensating for lost brightness of old lamps and dirty fixtures (strategies that bring the energy savings to 30-40%), solid-state ballast dimming systems can effectively take advantage of daylight and load-shedding strategies. The latter strategies can reduce energy consumption by another 30-40%. The total potential energy savings, considering the intrinsic 25% gain and all the other demand strategies, are 60-70%, relative to the best core-type ballast dimming system.

## COST OF CONSERVED ENERGY

The cost of conserved energy for the solid-state ballast is discussed and calculated in the last section of Part B.

## 3. WINDOWS

### *Advances in High-Performance Windows: The Successful Development of Low-Emissivity Coatings for Windows*

The annual resource energy used to heat and cool U.S. buildings equals three times the entire output of the Alaska pipeline (20).[5] One quarter of this is required to compensate for unwanted heat flow through windows. Windows are perceived as weak thermal links relative to insulated walls and roofs but this narrow perspective ignores potential window benefits.

In 1976, DOE initiated a program at LBL to develop guidelines for more efficient use of windows and to develop more energy-efficient window components and window systems. LBL researchers, under the direction of Stephen Selkowitz, set out to develop a window that would look like a window, admitting light, views, and useful solar heat, but behave thermally more like an insulated wall. They calculated that if a selective window coating could be developed that was transparent to visible light and solar radiation but blocked heat flow, energy loss through windows could be dramatically reduced.

In 1976 the principle behind such low-emissivity (low-E) coatings was understood, but no commercial low-E products were available. Some manufacturers knew about the potential of such coatings, but they doubted that durable products with adequate optical properties could be produced at low cost and high volume, so the R&D programs of the window industry essentially ignored low-E coatings. It was not until the federally funded research program at LBL demonstrated the promise of this technology that the window industry began to aggressively develop and ultimately market low-E products.

The $2 million federal investment went a long way, stimulating more than $100 million in private investment in low-E film production technology. In 1985, low-E window coatings were commercially available and saving consumers $14 million per year on their energy bills. By the year 2000, cumulative savings from low-E coatings used in the residential sector alone should be worth billions of dollars.

[5] Table 3-1 of (23) gives matrices for the residential and commercial buildings sectors, of energy end use by type of fuel, or electricity. Total heating and cooling adds up to 12 quads of resource energy. The Alaskan pipeline supplies nearly 4 quads, so heating and cooling uses 3 times this output.

This dramatic advance in window technology began with a series of research grants that LBL issued, with DOE funding, to several small research firms in 1976. Their task was to investigate potential coating systems and deposition processes for low-E films. LBL undertook studies to determine the optimal use of coatings in multielement window systems and to determine the potential benefits of these hypothetical windows in residences.

Coating technology consultants to LBL reviewed various deposition processes to determine if any had the potential to deposit the types of materials required for low-E coatings at high deposition rates and with good uniformity. A process known as magnetron sputtering appeared to meet the requirements and was gaining popularity during the late 1970s for small area coating in the electronics industry. The major U.S. producer of large magnetron sputtering systems, Airco Solar Products, was trying to sell these new large deposition systems to the U.S. glass industry for producing solar control coatings for architectural applications. At that time most glass producers used older vacuum coating systems that could not easily produce the uniform, multilayer low-E coatings. Based in part on the promising initial results of the DOE-supported studies, Airco accelerated its R&D program to develop suitable low-E coatings that could be licensed to the purchasers of its deposition systems. Airco had to do this work because many U.S. glass companies did not have the resources to undertake R&D on low-E coatings, and none had the sputtering systems capable of producing the coatings.

By the early 1980s, several large sputtering plants had been sold to major U.S. manufacturers, but none yet offered a commercial low-E product. In Europe, with its higher energy prices, more restrictive building standards, and a tradition of greater initial investment in buildings, several versions of low-E coatings had been successfully marketed.

At this time, LBL staff gave presentations at industry association meetings and trade shows, and met privately with research and marketing staff from a number of major window manufacturers to build confidence in low-E technology. LBL also developed new tables of heat transfer data for low-E windows, which were published in the 1985 ASHRAE Handbook of Fundamentals.

Interest and confidence in low-E coatings advanced when they were used in a small test building at MIT. Since low-E windows were one of several innovative building technologies being demonstrated in the facility, it was not possible to isolate the effects of the low-E glazing. However, many interested parties saw their first view of windows with low-E coatings at the test building.

*Market Breakthrough*

A major market breakthrough occurred in 1983, when Airco installed a large sputtering plant for low-E coatings for Cardinal IG, the firm that supplies the sealed insulating glass units for the largest window manufacturer in the United States, Andersen Corporation. This was the first time a large glass coater had been operated in the window industry by anyone other than a glass producer; Cardinal IG's move stimulated additional purchases of this type. Once Andersen announced the availability of a low-E window, the generic product gained new credibility in the eyes of consumers, builders, and specifiers, which placed pressure on other window manufacturers to supply low-E windows. In 1984 the first significant sales of low-E glass occurred; by 1985 industry estimated that 70 million square feet per year, or more than 5% of the market, had been captured.

By the mid-1980s, industry had invested millions in facilities that could produce the new generation of low-E coatings, and virtually every major glass and window company offered a low-E product. The marketing directors for several major glass firms estimate that 25-50% of the residential market could be low-E by 1990, a very high penetration rate for a new technology.

Although the product was originally developed with the northern residential market in mind, low-E coatings will also penetrate the residential sunbelt market and some fraction of the nonresidential building market. Traditional, high transmission low-E coatings can be modified to selectively transmit daylight but reject solar near-infrared energy to reduce cooling loads. In the sunbelt this modification offers control of winter heat loss and summer heat gain without excessive loss of view. This application represents a major new market opportunity.

In nonresidential buildings these modified low-E coatings will also make it easier for architects to use daylighting to save electric lighting energy and to reduce peak electrical demand charges. LBL simulation studies were the first to explore extensively the complex tradeoffs between daylighting benefits and heating and cooling loads and to make recommendations on the best coating types for different climates.

The proliferation of low-E coatings on the market is a sign of their commercial success, but it creates problems for designers and specifiers, who may be overwhelmed by confusing and conflicting data. LBL helped co-sponsor a Low-E Industry Roundtable in August 1985, at which more than 100 industry representatives expressed an interest in developing standardized calculation procedures so that low-E claims could be compared on a consistent basis. A new DOE/LBL microcomputer model, was released in response to that need. "WINDOW" allows users to quickly and accurately calculate the thermal properties of low-E windows of almost any design. Performance data from LBL field tests have also been used to help validate simulation models of low-E performance, to develop reliable design guidelines, and to gain the confidence of developers and specifiers of this new technology.

*Sales, Costs, and Savings*

An estimated 50 million square feet of low-E windows were sold in the United States in 1985 at a retail cost of \$2.00-3.00 per square foot more than normal double-glazed windows. These were primarily sputter coated on glass and plastic. Several U.S. glass companies have now introduced pyrolytic low-E "hard coats." These can be used on single glazing and in nonsealed multiple glazing units, thereby extending sales to the large retrofit market. The emittance properties of the pyrolytic coatings (with one exception) are not currently as good as those of the sputtered "soft coats." Additional coating research and development in the United States and overseas in the years ahead will continue to improve optical and thermal properties and cost factors. It should be possible eventually to reduce coating manufacturing costs to \$0.10-0.25 per square foot, which should reduce the additional retail cost to less than \$1.00 per square foot.

The potential energy savings from full market penetration of this technology are enormous. In the residential sector, windows with low-E coatings are now specified for new construction, additions, and renovations, a market with total annual window area sales of about 700 million square feet. The recent introduction of the pyrolytic hard coats provides additional opportunities in the retrofit market, such as storm windows and add-on glazings. The multitude of new low-E products and their varied potential applications makes it difficult to predict precisely their total energy-saving potential. It seems likely, however, that annual heating energy savings by 1995 will be worth more than \$400 million[6] and that cumulative energy savings through 2000 for the residential sector alone may total more than \$3 billion.

[6] We estimate total savings based on the following assumptions: a) existing stock is a mixture of single and double glazing; b) single can be replaced by single with low-E or by double with low-E; and c) double can be replaced by double with low-E or by other multiglazed and gas-filled configurations with low-E. For the residential sector, we calculate the improvement in heat transfer rate for each and derive an overall weighted average improvement of about 0.25 $Btu/ft^2$-hr-°F. Since our interest is in heating energy, we select a typical climate that is slightly colder than average. In a climate with 6000 heating degree days, the improved windows will reduce heat loss by about 35,000 $Btu/ft^2$-yr, which will save about 50,000 $Btu/ft^2$-yr after heating system efficiency (about 70%) is accounted for. At an average 1985 natural gas price of \$6.00 per million Btu, the savings is \$0.30/$ft^2$ per year. If industry projections of capturing more than 50% of the residential window market by 1995 are realized and if total annual residential window sales climb slowly to 800 million square feet, this would result in 1995 low-E sales of 400 million square feet. The annual heating energy savings are derived by multiplying the cumulative amount of

*Summary*

The U.S. Department of Energy invested approximately $2 million in research efforts to accelerate development and commercial introduction of low-E window technology. This helped leverage a much larger private-sector investment in new deposition systems and in development of new window product lines. Builders, architects, engineers, and homeowners are in turn investing to purchase and install these new systems. The ultimate benefits accrue to homeowners, in the form of lower utility bills and improved comfort and amenity; to the fenestration industry, in the form of new production technology, increased employment, and new value-added products; and to the United States, in the form of decreased dependence on imported fuel, an improved balance of payments, and maintenance of a strong building sector that can compete effectively in the international market. To individuals and to the nation, it makes sound economic sense to invest in this new energy-saving technology.

Over a 10-year period the DOE-supported fenestration research program has worked cooperatively with industry to introduce a new generation of high-performance window products. The successful market introduction of windows with low-E films is important because of their enormous energy savings and because they lay the foundation for further technological breakthroughs in window designs that are the subject of current DOE-supported research. In cold northern climates, a new generation of "superwindows" will have resistances of R-6 to R-10 and will outperform the best insulated walls or roofs. In the sunbelt and many nonresidential buildings, new "smart windows" will automatically adjust their transmittance properties to changing climatic conditions, to energy management requirements and to varying occupant needs, thus minimizing cooling needs, maximizing daylighting benefits, and providing the glare control, thermal comfort, and privacy desired by occupants. With these technology options and the appropriate design data to ensure their optimal use, windows and skylights have the technical potential of completely eliminating their net energy cost, becoming instead a net source of energy in buildings and saving consumers over $20 billion/year. Continued federal support of energy-efficient window research is vital to the achievement of this challenging and important national goal.

---

low-E sold by 1995, about 1.5 x $10^9$ ft$^2$, by the savings/ft$^2$ or 1.5 billion ft$^2$ x \$30/ft$^2$ = \$450 million. Actual savings will be larger since we neglect storm window retrofits and the higher value of savings in electrically heated homes and ignore potential cooling-load savings in the sunbelt. Low-E glazing use in the commercial sector will further increase savings. It seems likely, however, that annual heating energy savings by 1995 will be worth more than $400 million[6] and that cumulative energy savings through 2000 for the residential sector alone may total more than $3 billion.

## 4. BUILDING EQUIPMENT

*Introduction*

The objective of the Building Equipment Research (BER) program at Oak Ridge National Laboratory (ORNL), sponsored by DOE's Office of Buildings and Community Systems, is to develop a technology base for improving the energy efficiency and load characteristics of equipment for space heating and cooling, water heating, and other appliances used in residential and commercial buildings. This program has been sponsored by DOE since 1976. During the late 1970s and early 1980s, the philosophy of DOE and its predecessor, the Energy Research and Development Administration (ERDA), had been to work on projects that showed the potential for near-term commercialization of energy-efficient appliances. As a result of the research sponsored by DOE, a number of new products were developed and successfully marketed by manufacturers.

The change in administrations brought a change in philosophy within DOE, and the charter of DOE-sponsored research shifted to long-term, high-risk research with the potential for high payoffs. Under this philosophy, activities with near-term commercialization potential were phased out, and research shifted to equipment that might represent products to be introduced in the 1990s. Emphasis has been on high-risk activities not likely to be carried out by the private sector.

Below are five case studies. Three represent projects that were completed in the early 1980s, and resulted in more efficient products on the market. Two represent research that is currently under way and that, if successful, will result in new products in the 1990s. They represent clear cases in which DOE-sponsored research has been instrumental in accelerating the development of technologies. The DOE-sponsored research either produced the first product or prompted other manufacturers to enter the market, leading to further product improvements.

*Refrigerators*

In 1977, ORNL funded Arthur D. Little, Inc. to work with Amana Refrigeration, Inc. to design a high-efficiency refrigerator. From a list of 18 energy-saving options, six were chosen for the prototype model. These changes, including separate evaporators for the freezer and fresh food compartments, thicker cabinet insulation, improved door gaskets, relocation of the fan motor outside the freezer, and better defrost controls, resulted in a 60% reduction in energy use. Twenty-five prototypes were assembled and marketed to test consumer acceptance and field performance. Response was so positive that Amana began producing the new design commercially in 1981, selling more than 16,000 units by 1983 and producing net savings to consumers of more than $200,000 per year. Other manufacturers soon followed with their own high-efficiency refrigerators employing some of the options listed above.

While the Amana project was under way, ORNL also funded the Kelvinator Compressor Company to develop and field test 20 units of a prototype, high-efficiency refrigerator compressor. Since the compressor accounts for 70-85% of the energy demand of a refrigerator, improvements in this component were seen as critical to the goal of markedly improving overall appliance efficiency. By implementing several design changes in the motor and suction muffler, Kelvinator was able to increase compressor efficiency by 44%. The company manufactured 30,000 of these efficient compressors and then made a business decision to buy rather than manufacture its own compressors. Those 30,000 yielded annual savings of $12 each, repaying DOE's cost for the project every three years. Many other manufacturers, including a production facility in China, have since adopted similar high-efficiency designs.

*Heat Pump Water Heater*

The concept of a heat pump water heater (HPWH) is decades old, but until the 1970s energy prices were too low to justify such a heater's relatively high cost. In 1976, Energy Utilization Systems, Inc. (EUS) began to develop a residential HPWH, with assistance from DOE and ORNL beginning in 1977. By the end of 1978, EUS had completed design studies and had put 12 test units through a one-year laboratory performance evaluation. A concurrent marketing study by EUS indicated that an attractively short payback period could be achieved.

A 100-unit, year-long field test was then conducted with the cooperation of 20 electric utilities. This test, completed in 1980, produced useful information on the design and operating characteristics of these units. It also showed an installed average coefficient of performance (COP) of 1.93, compared to about 0.85 for conventional electric water heaters. EUS began producing HPWHs for sale in 1980, and was the first to market this product. Within a year, several other manufacturers offered HPWH units, and by 1984, 15 firms had entered the market. We believe the EUS project accelerated development of this market by two to five years. HPWH sales are still very modest, with 16,000 units sold in 1985. However, the gains have been substantial, with increases of 50% in 1984 and 33% in 1985.

*Heat Pumps*

ORNL has devoted about $9 million to cooperative research with manufacturers and industry R&D groups such as the Gas Research Institute and the Electric Power Research Institute to advance the efficiency of gas and electric heat pumps. These devices have the potential to heat and cool interior spaces more efficiently than conventional furnaces and air-conditioners. However, they rely on sophisticated thermodynamic cycles which have been difficult to engineer at low cost. ORNL has played a key role in identifying the most promising advanced designs and in supporting R&D with private firms to put these designs on the market.

Because the commercial heat pump market has been highly competitive in the past, with low profit margins, major domestic manufacturers have not devoted extensive resources to improving their products. General Electric and Westinghouse have both sold their HVAC (heating, ventilating, and air-conditioning) manufacturing businesses, presumably because of low profitability, and Borg-Warner is in the process of spinning off its HVAC division for the same reason. Many heat pump manufacturers are consequently turning to foreign suppliers for their components.

With ORNL support, several U.S. manufacturers, including Trane Corp., Carrier Corp., and Phillips Engineering, are on the verge of marketing gas-fired absorption heat pumps with coefficients of performance 40% greater than those of the best models available to date. These devices will trim $250-$300 per year from the average home's heating and cooling costs.

Electric heat pump efficiencies have recently been climbing by about 2.5% annually, but have still reached only 25% of their theoretical maximum efficiency. ORNL is now working with several firms to develop variable-speed compressors, and to reduce dynamic losses in frosting, defrosting, and cycling that have thus far kept advanced designs from reaching their full potential. It is too early to tell how much electric heat pumps can be improved, but the payoff from efficiency improvements already achieved is substantial.

Manufacturers acknowledge that federal R&D support has advanced heat pump development by two to five years, yielding the prospect of $17 billion in savings when high efficiency heat pumps saturate the space-conditioning market.

## 5. CALCULATION METHODOLOGY: COST OF CONSERVED ENERGY

An energy-efficient building or appliance is of no economic interest unless the value of the energy savings exceeds the additional cost of the investment. Here, we explain how we calculate the economics of investment in energy efficiency.

We assume that the consumer borrows the money for the efficient appliance or building and pays off the loan in a series of equal annual payments. We call the portion of his payments that covers the extra cost of greater efficiency an annual "surcost." Dividing the annual surcost by the annual energy savings tells how much the consumer is spending to avoid buying a unit of energy. We call this the cost of conserved energy (CCE), shown in line 4 of Table 1. Where the CCE is less than the cost of buying energy, conservation makes economic sense. The formula for CCE is:

$$\text{Cost of Conserved Energy (CCE)} = \frac{\text{annualized surcost}}{\text{annual energy savings}} \qquad 1.$$

The following example shows how the values on Tables 1 and 4 yield the cumulative net savings figures on line 9 of Table 4.

Consider solid-state fluorescent light ballasts, summarized in the first column of Tables 1 and 4. Line 1 of Table 4 tells us that one of these ballasts saves 100 kWh per year. Line 3 tells us that they last 10 years and line 4 tells us that they cost $12 more than conventional ballasts. Are they worth the extra cost? To find the answer to this question, we must first find the cost of conserved energy. Assume the $12 is borrowed from a bank for 10 years at a 7% real interest rate, where "real" means net of inflation. Line 5 then tells us that the "annual surcost" (annual bank payment on the loan) is $1.70. Equation 1 then gives

$$\text{CCE} = \frac{\text{Annualized surcost}}{\text{annual energy savings}} = \frac{\$1.70/\text{yr}}{100\ \text{kWh/yr}} = \frac{1.7\ \text{cents}}{\text{kWh}} \qquad 2.$$

which is rounded on Table 1, line 5 to 2 cents/kWh. A CCE of 2 cents/kWh is far cheaper than the average purchase price of electricity (7.5 cents/kWh). Thus, the more efficient ballast is an attractive investment. Half of the CCE entries on line 5 of Table 1 conserve natural gas instead of electricity. The CCE is expressed in dollars per million Btu and should be compared with an average building sector gas price of about $6/MBtu.

## CONVERTING ENERGY SAVINGS TO NET SAVINGS

The CCE tells us that the ballasts are a good investment. Next we want to calculate our net annual savings, which are simply the energy cost savings minus the annualized surcost.

$$\text{Net savings} = \text{energy cost saved} - \text{surcost} \qquad 3.$$

For ballast, the energy savings are 100 kWh/yr (line 1, Table 4). Assuming electricity prices of 7.5 cents/kWh, the gross savings are:

$$100 \text{ kWh/yr} \times 7.5 \text{ cents/kWh} = \$7.50\text{/yr} \qquad 4.$$

We already calculated that the annualized surcost for the ballasts is $1.70/yr. Thus,

$$\text{Net savings} = \$7.50\text{/yr minus } \$1.70\text{/yr} = \$5.80\text{/yr (line 6, Table 4)} \qquad 5.$$

By multiplying the net annual savings per unit (line 6, Table 4) by the number of units in the market at saturation, we calculate the net annual savings at saturation (line 7, Table 1).

Based on discussions with manufacturers, we estimate that federal R&D has advanced commercialization of the technologies described in this appendix by two to five years. Thus, the cumulative savings consumers will ultimately realize, purely as a result of the government's involvement, are simply the net annual savings at saturation times the number of years by which that technology was advanced through government R&D (Table 1, line 7 × line 3 = line 8).

References


1. Energy Res. Advisory Board (ERAB).1985. *Guidelines for DOE Long Term Civilian Research and Development.* Vol. 5, Dec. DOE/S-0042

2. US Dept. Energy. Off. Policy Planning and Analysis (DOE/OPPA). 1985. *Energy Use Trends in the U.S., 1972-1984.*

3. Solar Energy Research Institute (SERI). 1981. *A New Prosperity: Building a Sustainable Energy Future,* Cambridge, Mass: Brickhouse.

4. Meier, A., Wright, J., Rosenfeld, A.H. 1983. *Supplying Energy through Greater Efficiency: The Potential for Conservation in California's Residential Sector.* Berkeley, Calif: Univ. Calif. Press.

5. Geller, H.S., et. al. 1986. *Residential Conservation Power Plant Study.* Prepared for the Pacific Gas and Electric Co. Washington, DC: American Council for an Energy-Efficient Economy.

6. Public Utilities Commission of Texas (PUC). 1986. *Energy and Power Conservation in Texas Buildings.* Austin, Texas.

7. International Energy Agency (IEA). 1985. *Energy Policies and Programs of IEA Countries.* 1984 Review, OECD. Paris, France.

8. Piette, M.A., Wall, L.W., and Gardiner, B.L. 1986. "Energy Conservation—measured performance". ASHRAE Journal, 28:1, 72-78, Jan.

9. Geller, H.S. 1986. "Energy Efficient Applicances: 1986 Update," *Proceedings of the 1986 Summer Study on Energy Efficiency in Buildings,* Vol. 1. Washington, DC: American Council for an Energy-Efficient Economy.

10. Ross, M. 1985. Testimony at Hearings on Innovative Approaches to Industrial Energy Efficiency. Subcommittee on Energy Regulation and Conservation, Committee on Energy and Natural Resources, US Senate, Oct. 18.

11. Fahrenwald, P., Herendeen, R. 1982. "Energy efficiency supply curves for automobiles". Energy and Research Group Document #325. Champaign, Ill: Univ. Ill.

12. Bleviss, D. 1984. Testimony on Post-1985 Fuel Economy for Light Vehicles. House Subcommittee on Energy Conservation and Power, Committee on Energy and Commerce, July 31; study to be published in 1988 by Quorum Books, Westport, Conn., 06881.

13. Baldwin, S. 1986. "New opportunities in electric motor technology". IEEE Technol. Soc. Magazine, Vol. 5, No. 1, March.

14. Douglas, J. 1986. "Sealed in Silicon - The Power Electronics Revolution," EPRI Journal 11(9), Dec.

15. Schipper, L., Meyers, S., Kelly, H. 1985. *Coming in from the Cold: Energy-Wise Housing in Sweden.* Cabin John, Maryland: Seven Locks.

16. Ketoff, A.N. 1986. "Government spending for energy conservation R&D: a comparison of selected OECD countries". LBL-21185, Berkeley, Calif: Lawrence Berkeley Lab.

17. Agence Francaise pour la Maitrise de l'Energie (French National Energy Agency), 1986. Private communication with Olivier de la Moriniere.

18. Office of Conservation. 1986. FY 1988 Energy Conservation Multi-Year Plan. U.S. Department of Energy, July.

19. Sterling Hobe Corp. 1984. *Comparative Analysis of U.S. and Selected Foreign Household Appliance Industries.* Prepared for the US Dept. Energy, Building Equipment Div., Oct.

20. Baily, M.N., Chakrabarti, A.K. 1985. "Innovation and U.S. competitiveness." The Brookings Rev. 4(1), Fall.

21. Goldenberg, J., Johansson, T.B., Reddy, A., Williams, R. 1987. *Energy for a Sustainable World.* Wiley Eastern. In press.

22. U.S. Dept. Energy, 1987. *Energy Security: A Report to the President of the United States.*

23. U.S. Dept. of Energy, Office of Policy Planning and Analysis (DOE/OPPA). 1985. *Energy Use Trends in the U.S., 1972-1984.*

24. U.S. Dept. of Energy. Office of Conservation, 1987. *Energy Conservation Progress Success Stories.*

25. Garrett Corporation, 1987. Personal communication, Maxine Savitz.

26. Wisconsin Energy Conservation Corporation, 1984. *Low-Income Weatherization Program Study,* Madison, WI.

27. Rodberg, L.S., 1986. "Energy Conservation in Low-Income Homes in New York City: The Effectiveness of House Doctoring," Energy and Buildings, Vol. 9, No. 1&2, February/May 1986, pp. 55-64.

28. Alliance to Save Energy, 1987. Personal communications, Mark Hopkins.