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OPTIONS FOR REDUCING CARBON DIOXIDE EMISSIONS

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OPTIONS FOR REDUCING CARBON DIOXIDE EMISSIONS

ABSTRACT

Improvements in energy efficiency can significantly reduce the annual growth in greenhouse gas emissions. Such improvements occur when energy intensity is reduced; no reduction in energy services is required. Using the concept of "cost of conserved energy" to develop conservation supply curves similar to resource supply curves, researchers consistently find that electricity and natural gas savings of nearly 50% of current consumption are possible for U.S. buildings. Such reductions in energy consumption directly reduce emissions of greenhouse gases.

To capture these savings, we must continue to develop energy-efficient technologies and strategies. This paper describes three recent energy-efficient technologies that benefitted from energy conservation research and development (R&D) funding: high-frequency ballasts, compact fluorescent lamps, and low-emissivity windows. Other advanced technologies and strategies of spectrally selective windows, superwindows, electrochromic windows, advanced insulation, low-flow showerheads, improved recessed lamp fixtures, whitening surfaces and planting urban trees, daylighting, and thermal energy storage are also discussed.

INTRODUCTION

Worldwide combustion of fossil fuels produces enormous emissions of greenhouse gases. Annually, 5.7 gigatonnes of carbon (GtC), equivalent to one ton of carbon (C) for every living person on earth are pumped into the atmosphere to fulfill our energy needs. Carbon dioxide (CO_2) can be accounted for in either units of C or CO_2; one kilogram (kg) of C is equivalent to 3.667 kg of CO_2 [$3.667 = m(CO_2)/m(c) = 44/12$]. For this paper we have chosen to use CO_2.

Ideally, to reduce CO_2 emissions, we would cease energy production by fossil fuel burning facilities and switch to non-fossil fuel sources. However, the technical and economic barriers of the non-fossil sources must first be resolved. In the meantime, we can reduce about half of the annual growth in greenhouse gas emissions through increased energy efficiency in buildings, industry, and transportation.

Improvements in energy efficiency occur when energy intensity is reduced. Energy intensity is the ratio of energy consumed to the products and services produced, defined as:

$$\text{Energy Intensity} = \frac{\text{Energy (E)}}{\text{Gross National Product (GNP)}} \quad (1)$$

Energy efficiency does not mean a reduction in energy services; indeed the exact same services of heat, light, power, etc. are provided with technologies and processes that use less energy. In many cases, improvements in energy efficiency cost dramatically less than building new power plants or generating expensive peak power at existing facilities.

In the U.S., energy consumption is divided almost equally by three sectors: 1) industry, 2) transportation, and 3) commercial and residential buildings. After describing consumption trends of all of these sectors, we will focus on the building sector. We will discuss conservation supply curves that estimate the overall potential for energy and CO_2 savings and will describe specific energy-efficient technologies and strategies for this sector.

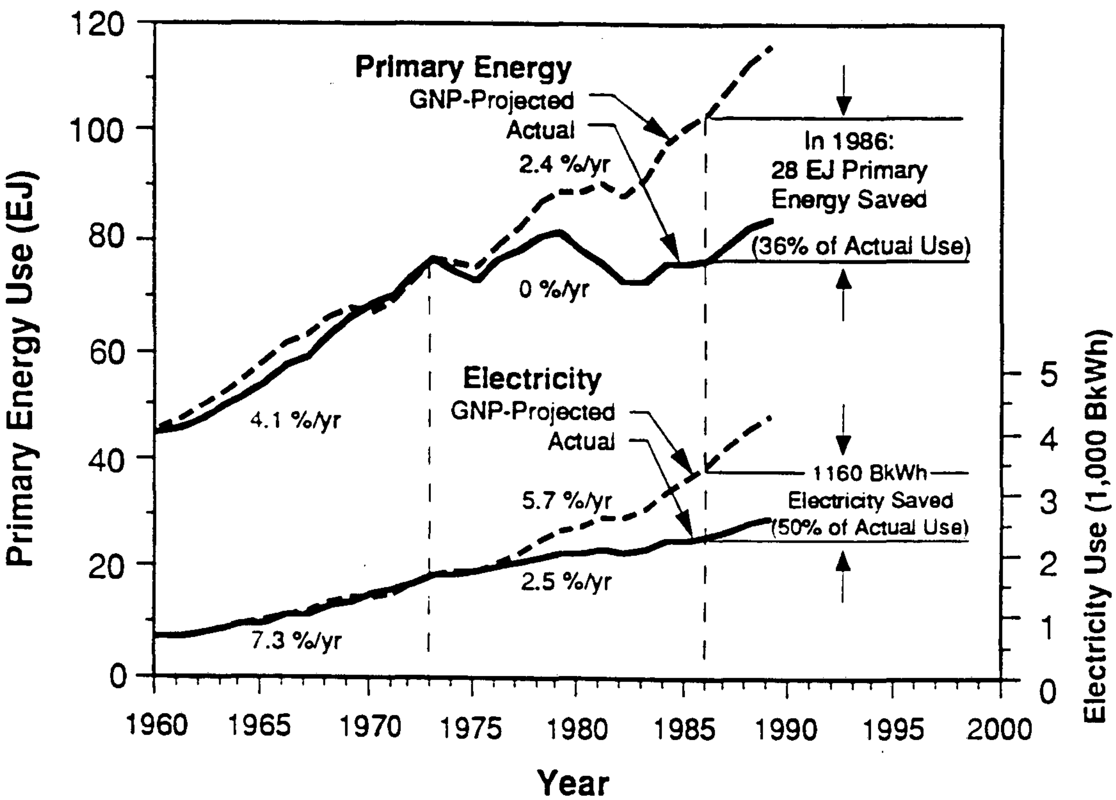


Figure 1. Total U.S. Primary Energy and Electricity Use: Actual vs. GNP Projected (1960-1989). GNP-projected energy values are based on 1973 efficiency and GNP. The electricity projections include an additional 3% per year to account for increasing electrification. Electricity use is given in terms of total equivalent primary energy input - exajoules (EJ) - on the left-hand scale, and net consumption - 1,000 billion kilowatt-hours (BkWh) - on the right-hand scale.

Source: Energy Information Administration, U.S. Department of Energy.

RECENT ENERGY CONSUMPTION TRENDS

During the past 30 years, primary energy consumption in the U.S. has fluctuated dramatically. These fluctuations are divided into three recent energy eras in **Figure 1**: the initial frozen energy efficiency era (1960-1973), the energy conservation era (1973-1986), and the current frozen energy efficiency era (1986-1989).

Primary Energy

Between 1960 and 1973, primary energy use and U.S. GNP were inexorably linked and climbed about 4% per year. In 1973, the Organization of Petroleum Exporting Countries (OPEC) oil embargo provided a powerful incentive to conserve energy; during the 13 years of high oil prices and progressive energy policies from 1973 to 1986, national energy use stayed constant, while U.S. GNP grew by a total of 35%, or 2.4% per year. Efficiency measures implemented during this period avoided an increase of approximately 50% in U.S. greenhouse gas emissions. By 1986, projected primary energy use was 36% higher that actual use, indicating a savings of 28 exajoules. One-third of this savings is attributed to structural changes in the economy and the remaining two-thirds is attributed to improved energy efficiency.[1] In 1986, when OPEC's oil prices collapsed, gains in energy efficiency nearly stopped. Now, primary energy consumption is climbing again at a rate of about 2% per year and it is feared that energy use and GNP could return to the lockstep relationship experienced prior to 1973, directly contributing to increased emissions of CO_2.

Electricity

Even more impressive than the past reductions in primary energy is the conservation experienced in electricity as shown in **Figure 1**. Since buildings consume two-thirds of total U.S. electricity, improvements in this sector contributed significantly to total electricity savings. Until 1973, total electricity use was growing at a rate of 7.3% per year (3% faster than the GNP). During the energy conservation era, electricity use grew only as fast as GNP, for an annual savings of 3.2%. In 1986, projected electricity use was 50% higher than actual electricity use. This savings, of 1160 billion kilowatt-hours (BkWh) per year, is equivalent to the annual output of 230 baseload (1000 megawatt) power plants. Using the 1989 all-sector average price of electricity of 6.4¢ per kilowatt-hour (kWh), this is a savings worth over $50 billion per year.

Residential and Commercial Buildings

Figure 2 shows the performance of residential and commercial buildings. During the energy conservation era between 1973 and 1986, energy use in this sector demonstrated the same remarkable "gaps" between actual and GNP-projected energy use. Actual energy use during this period was about 2% less per year than projected by GNP for both residential and the commercial buildings. In 1986, 8 exajoules (EJ), or 28% of the primary energy consumed in buildings, were saved (1 EJ = 10^{18}J). Using the 1989 cost of energy to buildings of $6.70 per gigajoule ($200 billion for 30 EJ consumed), this energy is worth over $50 billion and equal to four million barrels of oil per day (Mbod) of oil equivalent.

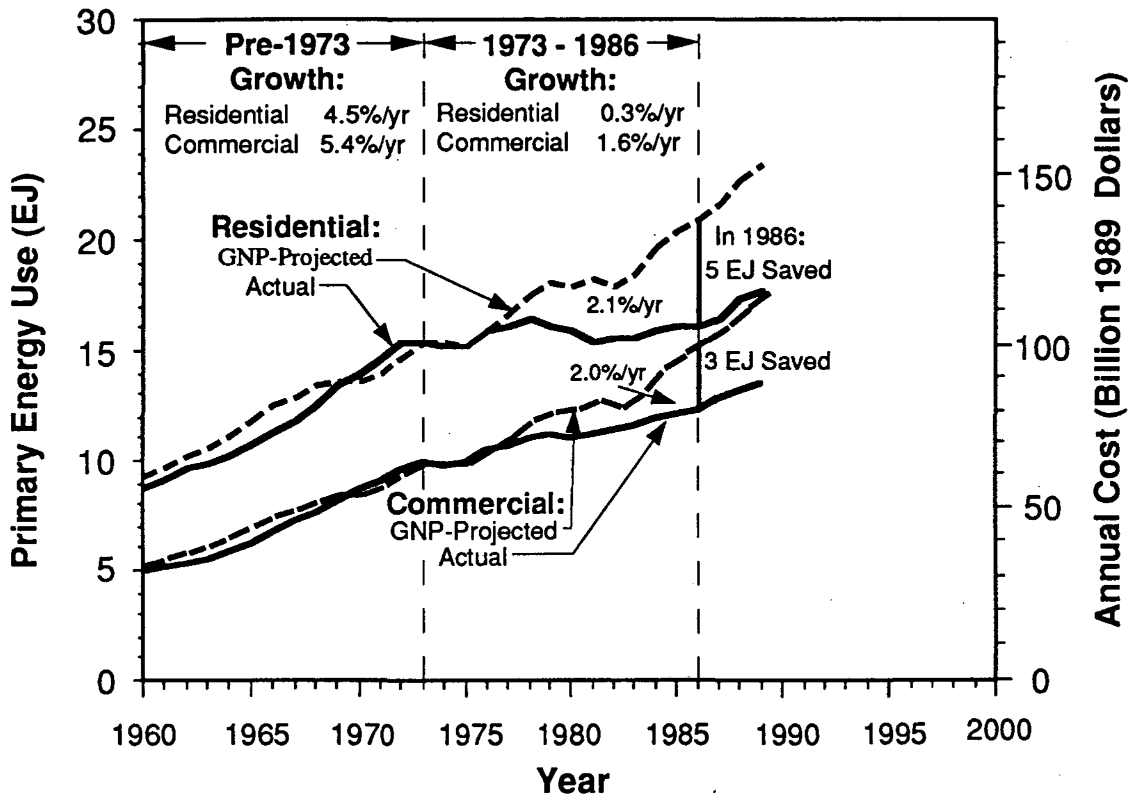


Figure 2. Primary Energy Use in U.S. Buildings (1960-1989). Before 1973, total primary energy use in residential and commercial buildings was growing at 4.5 and 5.4% per year respectively. From 1973 to 1986, energy use in residential buildings leveled off at about 16 exajoules (EJ) per year, while commercial building energy use grew only 1.6% per year from 10 to 12.4 EJ. Since the collapse of oil prices in late 1985, total primary energy use for both residential and commercial buildings has grown about 10%, or greater than 3% per year.

The residential GNP-projected curve is straightforward:

$$\text{Projected Energy (t)} = \frac{\text{Energy(1973)}}{\text{GNP(1973)}} \times \text{GNP (t)}. \qquad (1)$$

But for the commercial sector, the pre-1973 trend was for energy use to grow 1% faster than residential energy use (or GNP). Accordingly, the commercial GNP-projected curve has been tilted up by 1% per year to reflect this trend, i.e. (1) has been multiplied by the factor 1.01 (t-1973) ≈ 1 + .01 (t-1973).

Source: Energy Information Administration, U.S. Department of Energy.

CONSERVATION SUPPLY CURVES

A conservation supply curve relates energy savings achieved by implementing a given efficiency measure, to that measure's "cost of conserved energy" (CCE). Thus, for electricity:

$$\text{Cost of Conserved Energy (CCE)} = \frac{\text{Annualized Investment (\$ per year)}}{\text{Annual Energy Saved (kWh per year)}} \qquad (2)$$

The initial investment in an efficient technology or program is annualized by multiplying it by the "capital recovery rate" (CRR):

$$\text{CRR} = \frac{d}{1-(1+d)^{-n}} \qquad (3)$$

where "d" is the real discount rate and "n" is the number of years over which the investment is written off, or amortized.[2] We use "real" discount rate (i.e. corrected for inflation) in order to compare the CCE with the price of energy, excluding inevitable inflation from both measures.

For example, an energy-efficient refrigerator that consumes 690 kWh/year (or 240 kWh/year less than the 1990 average consumption of 930 kWh/year), has an incremental cost of about \$66.[3] Assuming a 6% discount rate and a 20 year amortization period, the CRR is:

$$\text{CRR} = \frac{.06}{1-(1+.06)^{-20}} = .09 \qquad (4)$$

and the CCE is calculated as:

$$\text{Cost of Conserved Energy (CCE)} = \frac{6 \text{ (\$ per year)}}{240 \text{ (kWh per year)}} = 2.5 \text{ ¢/kWh.} \qquad (5)$$

This cost can then be compared to the price of electricity to determine whether the investment should be made.

On a conservation supply curve, each measure or step (such as "efficiency improvements to residential refrigerators") is defined as follows:

Height = CCE (cents/saved kWh)
Width = annual kWh saved
Area under the step = total annualized cost of investment (\$)

The steps are ranked in order of ascending CCE, with the cheapest options plotted first, causing the curve to be upward-sloping.

Although conservation supply curves all have the same general shape, there are a number of underlying assumptions that can make them appear more or less attractive. These include the level of technology saturation assumed, the baseline and analysis period chosen, the number of new buildings included, whether existing efficiency is frozen or increases naturally, economic considerations such as retail vs. wholesale prices and discount rates, and whether fuel switching is included.

Traditionally, conservation supply curves have assumed one of two technology saturation levels: "technical potential" or "achievable." The "technical potential" saturation level is based on engineering and economic calculations without concern for the probability of successful implementation. "Achievable" saturation scenarios are based on actual experience; typical utility conservation programs have captured only about 50% of the technical potential. However, with recently adopted profit incentive mechanisms, some utilities can now earn up to 15% of avoided costs. Given this powerful profit motive to sell efficiency, the "achievable/technical" ratio will probably increase.

Conservation supply curves assume a specific baseline year and energy consumption level. They also address a specific analysis period (typically 10 to 20 years) and, depending upon the length of time, may or may not include new buildings. If new buildings are included, then the number of new buildings must be estimated. Also, existing levels of energy efficiency are either assumed to stay constant ("frozen efficiency") during the analysis period or to grow at a "naturally occurring" rate. In addition, economic assumptions, such as the discount rate, must also be made. An important economic assumption is whether retail or wholesale prices are used. Many utilities are now involved in promoting energy efficient technologies and are supplying products at wholesale prices, significantly reducing initial costs and payback periods. Finally, some conservation supply curves include fuel switching options to conserve electricity.

Electricity Conservation Supply Curves

LBL U.S. Residential Electricity Conservation Supply Curve

Analysts at Lawrence Berkeley Laboratory (LBL) have recently completed a comprehensive electricity conservation supply curve for U.S. residential buildings.[4] This curve was derived using a thorough database of appliance efficiency and costs developed for the U.S. Department of Energy (DOE) and a detailed analysis of thermal integrity measures in single-family dwellings. The LBL conservation supply curve evaluated the technical (versus achievable) potential for electricity efficiency improvements and assumed a 7% real discount rate, an analysis period of 1990 to 2010, and frozen efficiency. New buildings have been included. Conservation costs are those for consumer installation; utility or government administrative costs are not included.

Figure 3 shows the LBL technical potential conservation supply curve for residential electricity savings in 2010. For those measures costing less than the price of electric power to residential customers, or 7.6¢/kWh in 1989, the technical potential for residential electricity savings in all buildings in 2010 is about 40%, or 404 BkWh of 2010 baseline use of 1028 BkWh.

The LBL conservation supply curve is based on an analysis of 214 residential electricity conservation measures. This curve includes better equipment for space conditioning, appliances, and lighting. Fuel switching from electricity to natural gas for water heaters, ranges, and clothes dryers is also included. Further, engineering estimates for certain advanced technologies such as "superwindows," spectrally-selective glazings, evacuated panels for refrigerators, heat-pump water heaters, and heat-pump dryers are included. The LBL supply curve does not include "promising" technologies for which there are no data.

LBL Supply Curve Compilation

Analysts at LBL have also recently compiled and adjusted nine potential conservation supply curves that depict the technical potential for electricity savings for both U.S. residential and commercial buildings (which consumed 1627 BkWh or 64% of all 2630 BkWh sold in 1989) by about the year 2000.[5] LBL adjusted all curves to a real discount rate of 6%, to frozen efficiency, and to technical potential energy savings. All of these studies were based on available technologies; technologies that only exist as

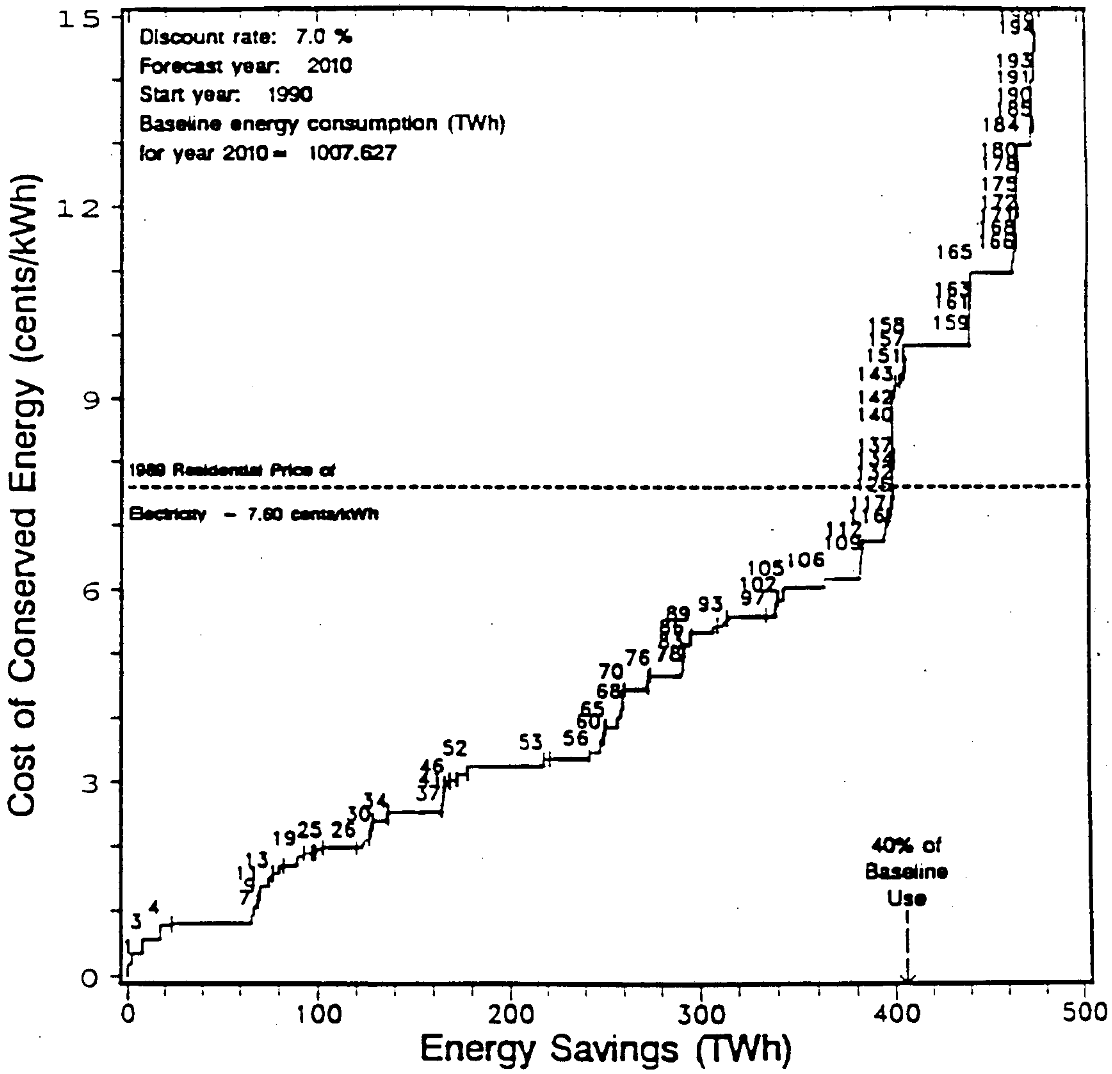


Figure 3. Supply Curve of Conserved Electricity for the United States Residential Sector - Maximum Technical Potential in 2010. Each step represents a conservation measure (or a package of measures). For example, step 36 is the conservation measure "improve refrigerator to 1993 standard," step 90 is "switch electric clothes dryer to gas," and step 154 is "improve windows in existing single family homes, North." The width of the step indicates the nationwide electricity savings from the measure and the height of the measure indicates the cost of conserved electricity. The end uses include space conditioning, water heating, refrigeration, lighting, and miscellaneous.

Source: J. Koomey, C. Atkinson, A. Meier, J. McMahon, S. Boghosian, B. Atkinson, I. Turiel, M. Levine, B. Nordman, and P. Chan, *The Potential for Electricity Efficiency Improvements in the U.S. Residential Sector*, LBL-30477, (Lawrence Berkeley Laboratory, Berkeley, 1991).

prototypes were excluded. Cumulative electricity savings of the conservation supply curves range between 35% and 55%. Other conservation supply curves that include technologies that are now only prototypes will undoubtedly result in larger technical potential savings.

Figure 4 presents the 12-step Electric Power Research Institute (EPRI) curve which represents the approximate mid-range of the compiled supply curves. (The EPRI curve actually includes only 11 steps; an additional first step for white surfaces and urban trees has been added by LBL.) The EPRI curve represents a cumulative savings of 734 BkWh, which is 45% of 1989 U.S. building sector electricity use.[6] The EPRI curve is also consistent with a new National Research Council study[7] which is too coarse to compile as a supply curve. That study (in its Table 4-12) estimates a near term retrofit potential savings of 30% and a long term retrofit potential savings of 50%. These potential savings nicely bracket the EPRI potential savings of 45%.

Natural Gas Conservation Supply Curves

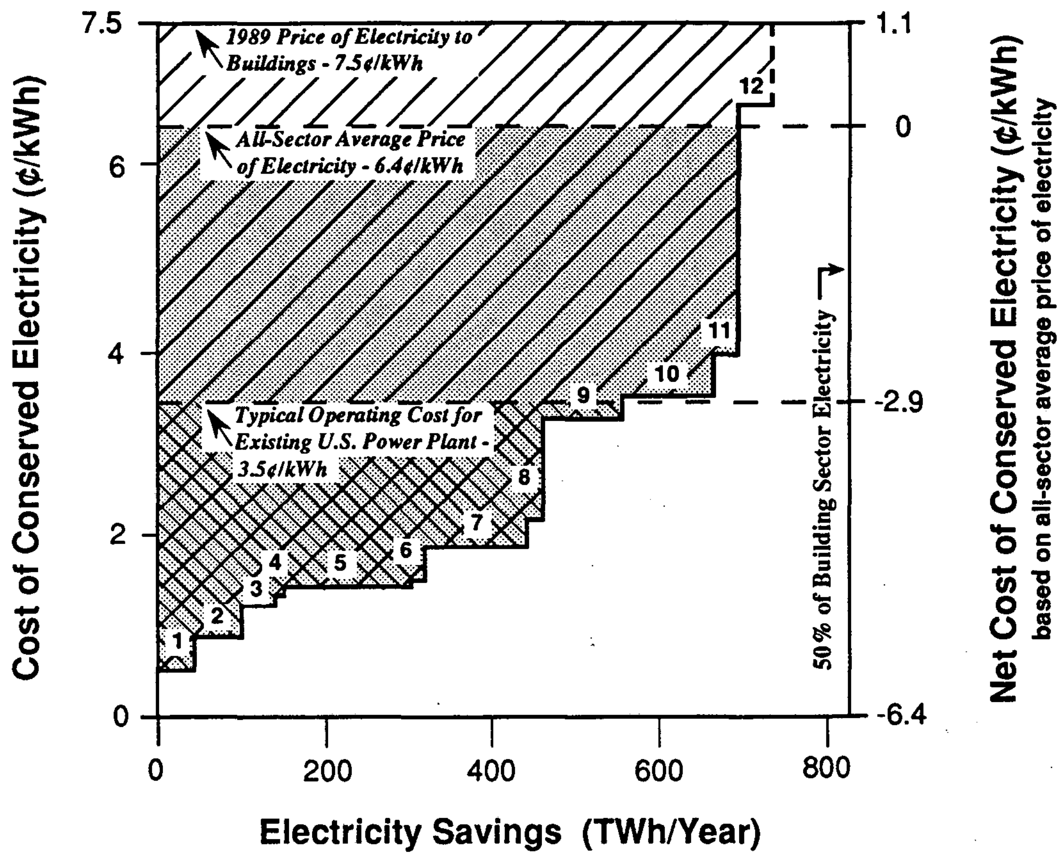
LBL has also reviewed two supply curves of conserved natural gas for the residential sector. One is a study of the U.S. residential sector by the Solar Energy Research Institute[8] and the other is a study of the California residential sector.[9] **Figure 5** presents these two supply curves and shows savings of about 50% are possible for U.S. residential natural gas use at less than the 1989 average price of $5.63 per million Btu. Extrapolating this estimate to cover all gas and oil use in U.S. buildings yields savings of about 5.2 quads. (Natural gas and oil are interchangeable for many utilities and industries, so we combine these two fuels together to estimate potential fuel savings.)

From these studies it appears that potential natural gas savings are slightly larger than electricity savings. However, natural gas savings are not well studied, presumably because less is spent annually in the U.S. on natural gas (about $60 billion versus about $140 billion for electricity) and because even during high energy prices natural gas use stayed constant while electricity use grew.

Fuel Switching

Assuming that electricity is generated from the mix of fuels burned by U.S. power plants (including coal with its high C content), then fuel switching from electricity to natural gas represents another method to reduce CO_2 emissions. In the building sector, fuel switching involves replacing electric resistance heat with on-site combustion of natural gas and replacing electric appliances with gas appliances (mainly water heaters and clothes dryers). Fuel switching is the least well studied U.S. potential conservation option. Even so, we estimate that U.S. buildings electricity use could be reduced by 10% through fuel switching.[10]

As an example of fuel switching we will discuss residential water heaters which represent the largest single U.S. potential switch. In Michigan, 400,000 homes had gas heat but electric resistance water heaters, and could switch with a simple payback time of 2 years. In the 1988 Michigan Electric Options Study, the switching potential was about 20% of residential electricity. Because Michigan seems to have a higher fraction of homes with gas available than does the rest of the U.S., we have picked a symbolic 10% reduction in U.S. building electricity, and used the data for water-heaters as a proxy for all fuel switching.[11] In this example, 163 BkWh of electricity (10% of the building sector 1989 consumption of 1627 BkWh) are replaced by 0.7 quads of natural gas. Such a fuel switch ultimately reduces CO_2 emissions because natural gas contains emits less CO_2 than the mix of fuels used to produce electricity.



Potential Net Savings:

$ 37 B/yr. - CASE 1: Below 7.5¢/kWh 1989 Price of Electricity to Buildings

$ 29 B/yr. - CASE 2: Below 6.4¢/kWh All-Sector Average Price of Electricity

$ 10 B/yr. - CASE 3: Below 3.5¢/kWh Typical Operating Cost for Existing U.S. Power Plant

Figure 4. Cost of Conserved Electricity (CCE) for Buildings. This figure is the EPRI curve with a discount rate of 6%. The full X-axis corresponds to 813.5 TWh, which is half of the total 1989 U.S. buildings electricity use of 1627 TWh and which cost $140 B. The Net CCE scale is displaced by 6.4 ¢/kWh - the all-sector average price of the avoided electricity. All recommended measures that have a CCE of less than 6.4¢/kWh have a negative cost, i.e. save money.

Areas between the CCE and a price line represent annual dollar savings. Case 1 (lightly hatched area) shows this potential annual net savings of $37 B, based on the average price of the avoided electricity of 7.5¢/kWh. Case 2 (shaded area) represents the potential annual savings of $29B, based on the all-sector average price of 6.4¢/kWh (defined as Net CCE of 0 on the right hand scale). To be extremely conservative, the net CCE can be referenced to the avoided cost of merely operating an existing plant - about 3.5 ¢/kwh at the meter. Case 3 (heavily hatched area) represents this most conservative estimate of savings of $10B/year.

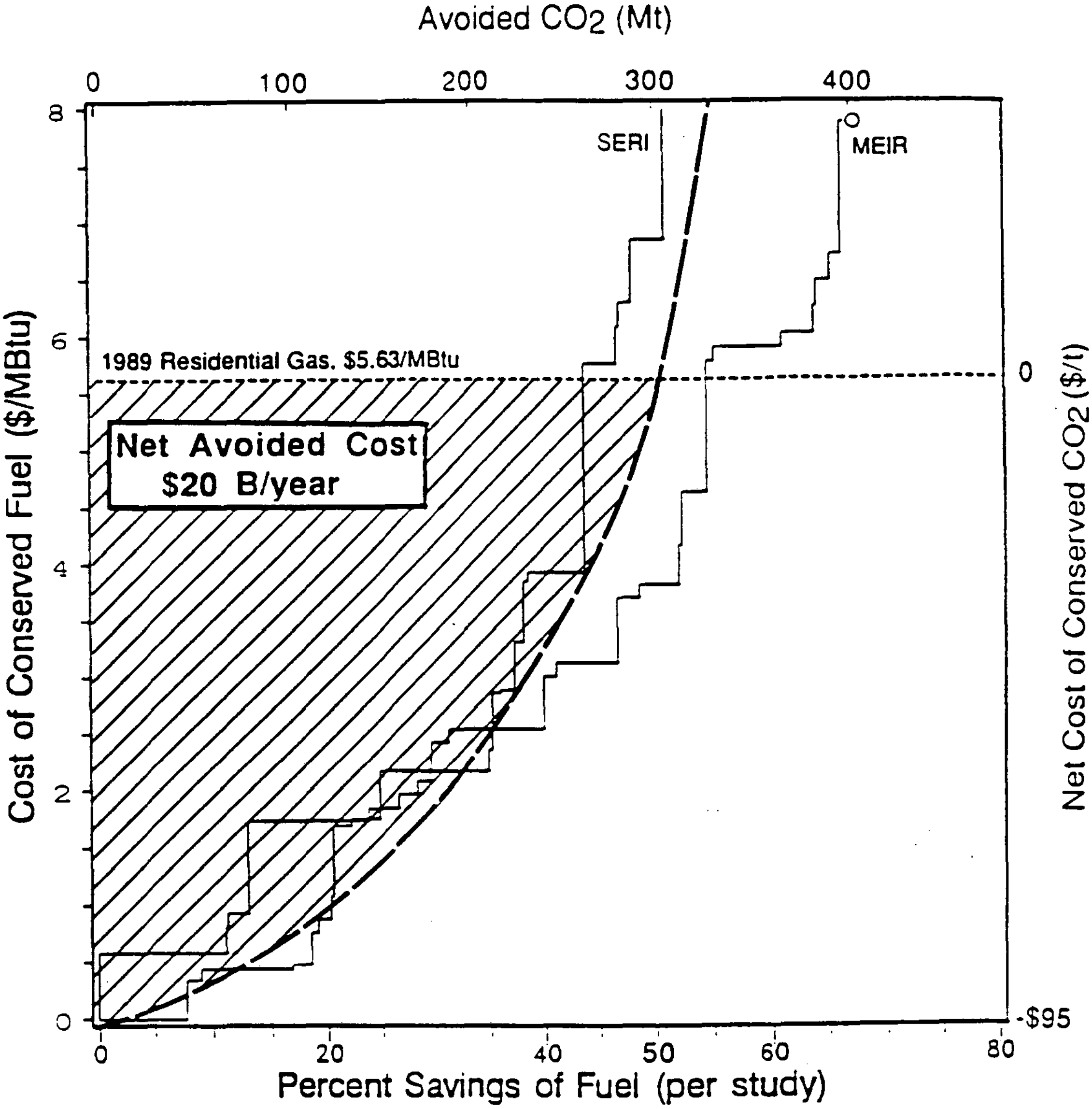


Figure 5. Cost of Conserved Energy (CCE) and Net Cost of Conserved Carbon Dioxide (CC CO_2) for the Residential Sector. The figure shows two supply curves of conserved natural gas for the residential sector: a study of the U.S. residential sector by the Solar Energy Research Institute and a study of the California residential sector by Meier, et al. The smooth curve between them goes through 50% savings at the current average price of $5.63/MBtu for natural gas. Extrapolating this to natural gas and oil use for the entire buildings sector yields a potential savings of about 5.2 quads of "fuel." The right-hand y-axis scale shows the net CC CO_2 running down from 0 to -$95/t CO_2, and the average CC CO_2 is -$70/t CO_2. The potential CO_2 savings are about 300 Mt CO_2.

Sources: Solar Energy Research Institute (SERI), *A New Prosperity: Building a Sustainable Energy Future* (Brickhouse Publishing, Andover, MA, 1981) and A. Meier, J. Wright, A. Rosenfeld, *Supplying Energy Through Greater Efficiency: The Potential for Conservation in California's Residential Sector,* (University of California Press, Berkeley, 1983). CCEs for SERI curve are based on 6% discount rate and 10-year lifetime and are approximated from the original CCEs that were based on a 3% discount rate and slightly different lifetimes. CCEs for MEIR curve are calculated using known lifetimes.

Table 1 shows that, for this example, 114 Mt CO_2 produced by electricity are replaced by 40 Mt CO_2 produced by natural gas, with a net savings of 74 Mt CO_2.

Fuel switching as an electricity conservation policy is now attracting interest in several locations. In Vancouver, Canada, BC Hydro gave subsidies to consumers to replace electric water heaters with gas units. In Vermont, winter-peaking utilities have begun fuel switching programs that promote switching from electricity to natural gas or propane. These utilities audit electric customers to determine if they are eligible for fuel switching and, if so, arrange and oversee the switch. Because of this program, alternative fuel dealers are offering financial incentives to attract new customers. The utilities are also offering incentive payments and have completed low-income rehabilitation projects.[12] Other New England utilities are being encouraged to establish fuel-switching programs. In Wisconsin, the Wisconsin Public Service Commission has directed utilities to fuel switch where economic.

Table 1. A fuel switching example of saving 10% of building sector electricity by switching water heaters from electric resistance to gas heat.

	1989 Use	1989 Potential Savings
Electricity		
BkWh (10% of Buildings BkWh)	1627	163
Mt CO_2 ($1kWh_e = 0.7$ kg CO_2)	1139	114
$ (6¢/kWh x 163 BkWh)	--	$9.8B
Gas		
Quads (.0043 MBtu replaces $1kWh_e$)	10.4	-0.7Q
Mt CO_2 (1Q = 57 Mt CO_2)	600	-40
$ (at average $4.20/M Btu)	--	-$3.0B
Net		
Mt CO_2	1739	74
$	$170B	$6.8B

OVERALL ENERGY AND CARBON DIOXIDE SAVINGS POTENTIAL

The studies described above indicate large potential savings in the U.S. building sector of about 45% of electricity and about 50% of natural gas. Further electricity savings are possible through fuel switching.

Table 2 characterizes these energy savings as dollar savings to the U.S. economy. First, using the 1989 all-sector average price of 6.4¢ per kWh, the potential electricity savings using the EPRI residential and commercial buildings estimate of 734 BkWh have a net value of $29 billion (taking the cost of the efficiency measures into account). Second, using the 1989 residential average price of natural gas of $5.63 per MBtu, the potential natural gas savings of 5.2 quads have a net value of $20 billion. When fuel switching savings of $6.8 billion are added, the total technical potential energy savings is valued at $56 billion.

Potential energy savings may also be characterized as savings of CO_2 emissions. For electricity we make this conversion using the CO_2 produced by the mix of fuels burned by U.S. power plants,[13] which is estimated to be 500 million tonnes (Mt) of carbon (C) for 1990 electric sales of 2610 BkWh, or 0.19 Mt C/BkWh. One kilogram (kg) of carbon is equivalent to 3.667 kg of CO_2, so 0.19 Mt C = 0.7 Mt CO_2. Thus:

$$1 \text{ kWh} = 0.7 \text{ kg } CO_2 \qquad (6)$$

and

$$1 \text{ BkWh} = 0.7 \text{ Mt } CO_2. \qquad (7)$$

Using (6), the cost of electricity is then converted as follows:

$$1¢/\text{kWh} = \$14.3/\text{t}CO_2. \qquad (8)$$

Using (8), net CCE can be converted to the net cost of conserved CO_2, or CC CO_2.

In order to transform fuel savings to CO_2 savings we add the CO_2 that oil and natural gas contribute to our base case fuel use in buildings. In 1989, natural gas accounted for 7.7 quadrillion Btu (quads) and oil accounted for 2.7 quads. Weighting these fuels by their respective carbon content, assuming natural gas contains 14.5 kgC/MBtu and oil contains 20.3kgC/MBtu,[13] yields:

$$\begin{gathered} 1 \text{ MBtu "fuel"} = 16 \text{ kg C} = 59 \text{ kg } CO_2 \\ \text{or} \\ 1 \text{ quad "fuel"} = 59 \text{ Mt } CO_2 \end{gathered} \qquad (9)$$

Overall potential savings from electricity and fuel efficiency improvements along with fuel switching are summarized in Table 2. Total net CO_2 savings are 890 Mt, or slightly over 50% of 1989 emissions from this sector of the U.S. economy.

Table 2. Summary of the Potential Savings of Electricity, Fuel (Gas and Oil), and Carbon Dioxide for Existing Buildings.

	1989 Use	1989 Potential Savings
Electricity		
BkWh	1627	734
Mt CO_2 (1kWh$_e$ = 0.7 kg CO_2)	1139	513
$ (at 7.5¢/kWh)	$112B	--
Net $ (at 6.4¢/kWh)	--	$29B
CC CO_2 ($/t)	--	-57
Fuel (Gas and Oil)		
Quads	10.4	5.2
Mt CO_2 (1M Btu - 57 kg CO_2)	600	300
$ (at $5.63/M Btu)	$58B	--
Net $ (at $5.63/M Btu)	--	$20B
CC CO_2 ($/t)	--	-70
Fuel Switching (from Table 1)		
Net Savings from Switching 10% of Electricity to Gas		
Mt CO_2 (Electricity and Gas)	1739	74
Net $	--	$6.8B
Net CC CO_2 ($/t)	--	-92
Total		
Mt CO_2	1739	890
Net $	$170B	$56B
Net CC CO_2 ($/t)	--	-63

ENERGY EFFICIENCY RESEARCH AND DEVELOPMENT

Need For Increased Funding

Conservation supply curves indicate that the technical potential exists for energy and CO_2 savings of close to 50% of current consumption levels in the U.S. building sector. But how can such large savings be realized? First, we must continue to develop energy-efficient technologies and strategies to capture these savings. Then we must ensure widespread adoption of existing and new technologies and strategies through development of effective energy policies. Adequate funding for energy efficiency research and development (R&D) is an *essential* element of this picture.

Current energy conservation R&D funding, however, is wholly inadequate. In 1989 U.S. public domain R&D for efficiency was approximately $200 million, less than 10% of public domain R&D spending for all U.S. energy technologies. **Table 3** sets the scale:

Table 3. R&D Spending Comparison

R&D	Spending	Comments
Total U.S.	3% of U.S. GNP	
Non-military	2% of U.S. GNP	
Mature industries	1% of revenues	
Public domain energy efficiency	0.04% of U.S. energy sales	(2/5000 of bills of $500 B/yr.)
Building energy efficiency	0.025% of utility revenues	(1/4000 of bldg energy of $200 B/yr.)

Figure 6 shows a time-series of public domain R&D spent on energy technologies in fields including efficiency, renewables, fossil fuel, nuclear power, and magnetic fusion.[14] In 1978, public energy efficiency R&D reached $250 million, only 5% of all energy R&D, and it remained at this level throughout fiscal year 1991. This level of spending is .04% of U.S. energy sales from annual energy expenditures of $500 billion. In 1991, under the Bush administration, energy efficiency R&D spending <u>did</u> grow from $200 million to $265 million, still extraordinarily out of step with the dramatic economic contribution of energy efficiency.

Figure 7 compares the energy performance of various energy sciences to their DOE funding. Between 1973 and 1989, 22 exajoules (EJ) of primary energy were saved as a result of energy efficiency improvements. When divided into the 1991 budget for energy efficiency of $200 million, energy efficiency gets only $9 million per EJ that it has contributed. In comparison, fossil fuel-related R&D, with its strong political muscle, receives $328 million per EJ supplied, and nuclear power, with its devoted administrative and congressional support, gets $78 million per EJ supplied. Energy efficiency R&D is probably neglected because there is no perception of political muscle (apart from transportation) either by the fragmented building sector and industry or by the Congress. An added problem is that many policymakers honestly feel that since efficiency is such a success compared to fossil fuel, nuclear, and renewables, it can take care of itself and needs little help from the government.

Of the total $200 million per year for efficiency shown in Figures 6 and 7, buildings-related R&D gets only $50 million per year. Compared with annual energy expenditures of $200 billion, that's only 1/4000 of revenues, despite the dramatic economic growth achieved by efficiency improvements, the escalating threat of global warming, and the huge successes of simple, affordable energy technologies such as those we will discuss later in this chapter. Furthermore, the highly-fragmented industry invests very little in private R&D -- the majority of builders and component

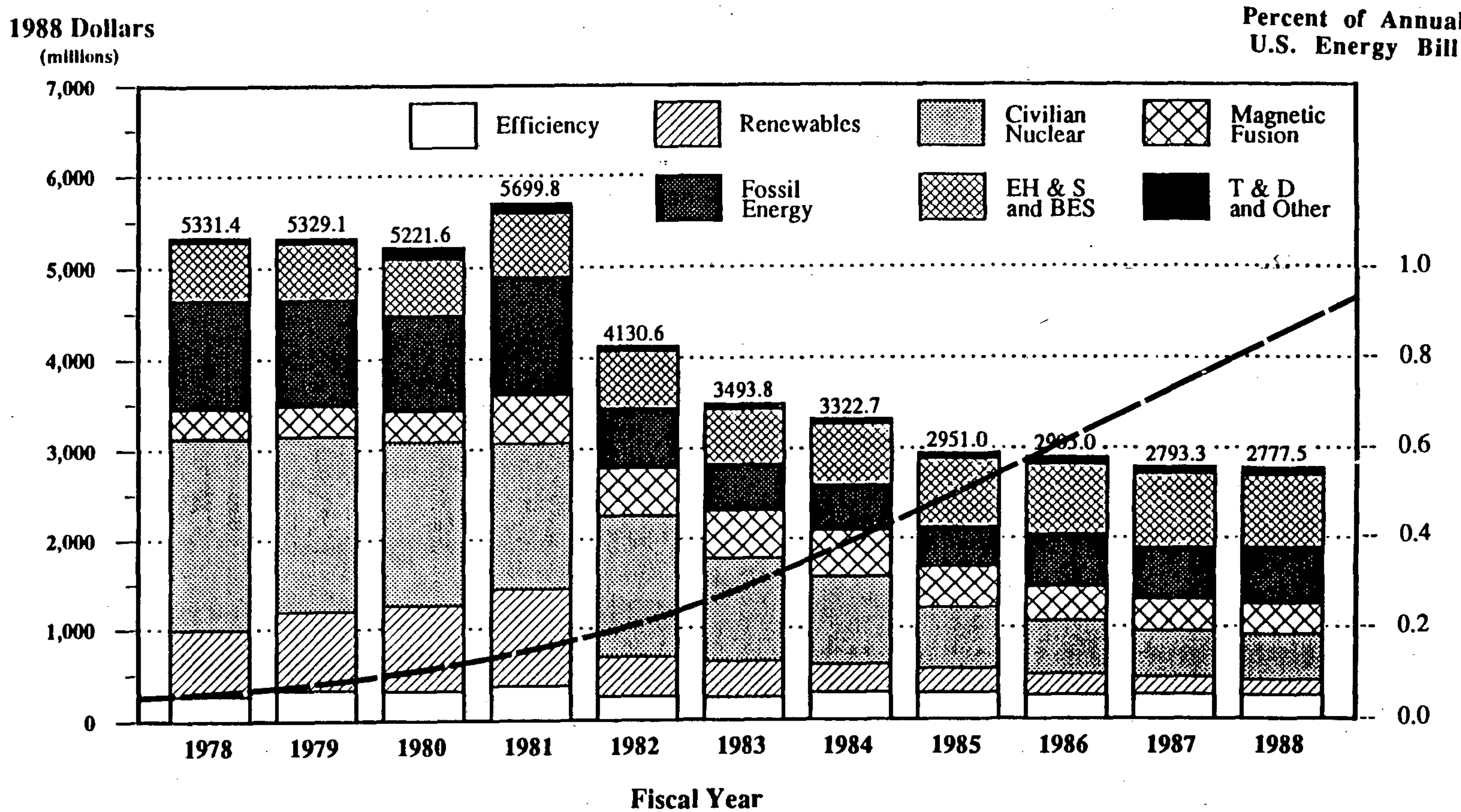


Figure 6. **Combined energy technology R&D budgets (DOE, EPRI, GRI, and USNRC), in millions of 1988 dollars, for efficiency improvement; various energy sources; environment, health, and safety (EH&S) research; basic energy sciences (BES); and "T&D and other." The latter includes GRI and EPRI funds for transmission, transportation, and distribution and planning and management functions.** *Sources:* DOE, FY 1988, derived from summaries of the *House-Senate Conference Report on the DOE Budget*, which appeared in *Inside Energy*, Jan. 4, 1988. DOE, FYs 1978-87, *Appendix to the Budget of the U.S. Government, 1980-1989; Department of Energy Congressional Budget Request; Department of Energy Budget Highlights*; Department of Energy Budget Formulation Office, personal communication. EPRI, Annual Reports of the Electric Power Research Institute; and Research and Development Plans. GRI, Five-Year Research and Development Plans and Program; and Gas Research Institute Annual Reports. USNRC, *Appendix to the Budget of the U.S. Government, 1980-1989.*

Source: Oak Ridge National Laboratory, *Energy Technology R&D: What Could Make A Difference?* (ORNL-6541/V1), May 1989.

Dashed line shows how energy efficiency R&D spending should have increased to about 1% of U.S. energy sales by 1988, comparable to R&D spending levels in mature industries.

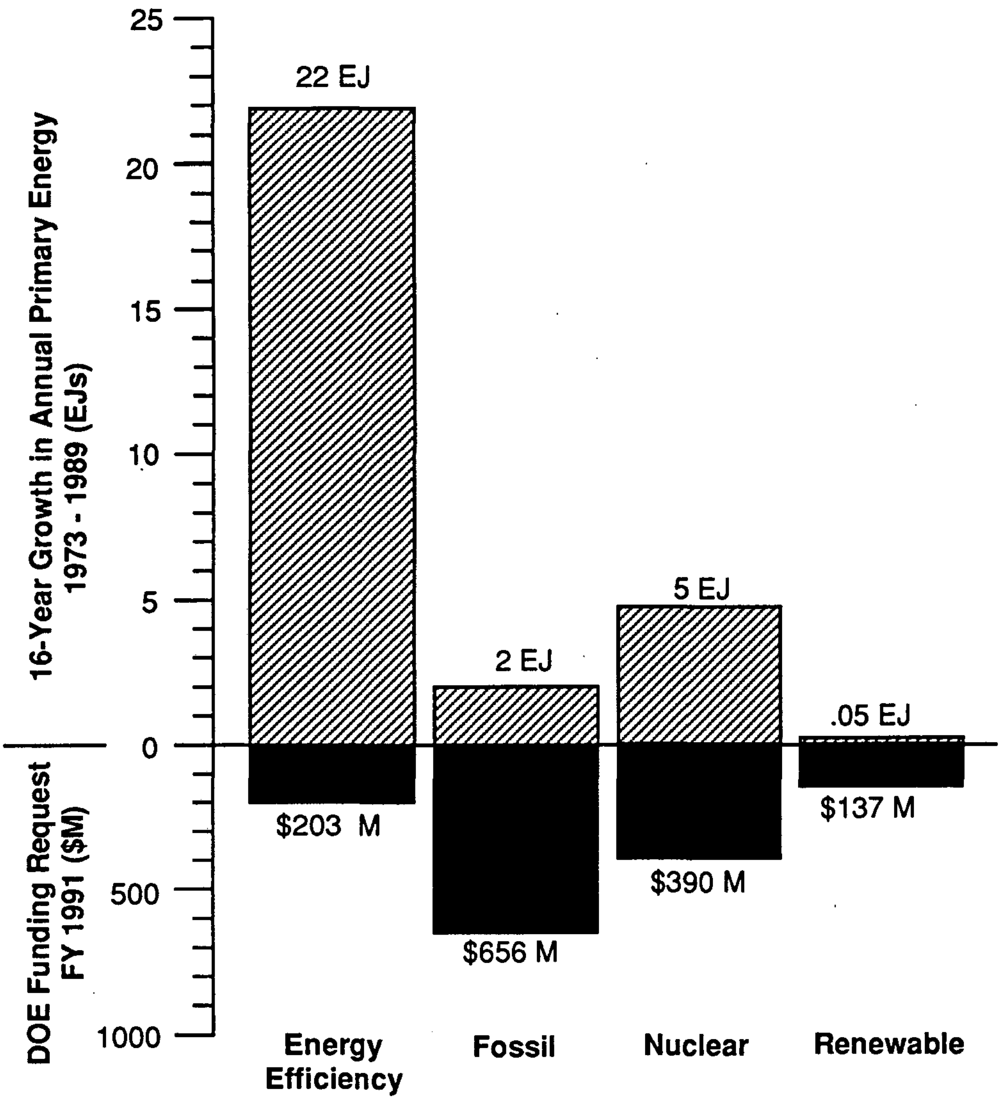


Figure 7. Growth in Annual Primary Energy Supplied or Saved by Energy Efficiency (1973-1989) vs. DOE FY 1991 Funding Request. 22 exajoules (EJ) of primary energy were saved as a result of energy efficiency improvements between 1973 and 1989. If efficiency is measured as the difference between actual 1989 energy use and energy use projected by a constant 1973 E/GNP, then full efficiency gain would be approximately 33 EJ. However, structural change is credited with 1/3rd of the change, resulting in an energy efficiency value of 22 EJ. Despite the fact that 22 of the 29.5 EJ of primary energy were provided through energy efficiency, this source is allocated only $200 million of the $1.4 billion budget.

Sources: Funding Data: DOE/MA-0400, *U.S. DOE Posture Statement and FY 1991 Budget Overview*. Energy Data: DOE/EIA-0384, *Annual Energy Review* 1989. Structural Change: L. Schipper, R.B. Howarth, H. Geller, *Annual Review of Energy*, Vol. 15, 1990 and U.S. Office of Technology Assessment, *Energy Use and the U.S. Economy*, June 1990.

manufacturers are simply not large enough to do research or to lobby effectively for increased governmental R&D funding.

In order to optimize the potential benefits of energy efficiency in buildings, the U.S. federal government should follow the example of Sweden which has a nationally-funded council for buildings research whose funding is equivalent to $1 billion U.S. The results of such an energy efficiency commitment are twofold. First, Sweden leads the world in energy-efficient buildings and second, its building sector runs an annual international trade surplus equivalent to $60 billion U.S. The U.S. building sector's performance is dismal in comparison, with a trade deficit of $6 billion per year.[15]

Research and Development Successes

During the past decade, significant strides have been made in the development of energy-efficient technologies. **Table 4** provides a summary of the characteristics and economics of three energy-efficient technologies that will be described in this section: high frequency electronic ballasts, compact fluorescent lamps, and low-emissivity windows.[16] These technologies, which were developed with DOE R&D funding, illustrate the remarkable benefits-to-R&D-cost ratios that can be realized with energy-efficient technologies.

Lighting: Fluorescent versus Incandescent

The visible light output of lamps is measured in units of "lumens" and the "efficacy" of lighting is measured in lumens/watt. Thus, 40, 60, or 100 watt incandescent lamps have efficacies of 13, 15, or 17 lumens/watt. Fluorescent lamps, by contrast, are 4 to 5 times more efficient. Thus, 34 or 40 watt fluorescent lamps (four feet long) are 60 to 80 lumens/watt (including ballast losses) depending on whether their ballasts (which start them and limit their current) are of the older "core-coil" type or of the recently developed high-frequency, electronic type.

Now we can understand U.S. lighting in 1973, just before the OPEC oil embargo provoked the sudden rise in electricity prices. With their 5-fold advantage in efficiency, fluorescent lamps had taken over commercial buildings, most frequently with "cool white" (sunlight colored) phosphors. A typical fixture, with 2 lamps of 40 watts each, yielded about 6000 lumens, equivalent to 5 incandescents of 75 watts each. The smallest fluorescent on the market at the time was the 22 watt "circline" (890 lumen) equivalent to a 60 watt fluorescent, but (with end losses) its efficacy was down to 40 lumens/watt. These fluorescents were fiercely resisted by homeowners and decorators who preferred the nostalgic, reddish, 15 lumen/watt incandescent.

Thus, in 1973, about 200 BkWh out of U.S electric sales of about 2000 BkWh,went to fluorescents (for 80% of the lumens) and 200 more BkWh went to incandescents (for most of the remaining lumens). As electricity prices shot up, two developments became inevitable: first, improve fluorescents (with high-frequency ballasts), and second, develop 20 watt compact fluorescents (with "warm red phosphors if necessary) to screw into the sockets then filled with 50-75 watt incandescents. This compact fluorescent lamp development was jump-started when high-frequency ballasts were shown to economically cut end losses and ballast losses in half.

Electronic Ballasts

Fluorescent lamps typically have 6 milli-torr of mercury (Hg) vapor, "buffered" by 1-3 torr of noble gas (argon or krypton). The Hg is about 1% ionized during operation, and emits mainly ultraviolet photons, which excite a "phosphor" coating on the inside of the glass tube, which in turn radiates visible light. In the middle of the

Table 4. Economics of Three New Energy Efficiency Technologies and Appliance Standards. An update of Tables 1 & 4 of Geller et al., *Ann. Rev. of Energy* 12, 1987.

	RESEARCH & DEVELOPMENT				STANDARDS
	HIGH FREQUENCY BALLASTS VS. CORE COIL BALLASTS	COMPACT FLUORESCENT LAMPS (1) VS. INCANDESCENTS	LOW-E (R-4) WINDOWS VS. DOUBLE GLAZED WINDOWS Per small window (10 ft^2)	TOTAL	REFRIGERATORS AND FREEZERS '76 base case vs. '85 CA Stds.
1. UNIT COST PREMIUM					
a. Wholesale	$8	$5	$10		
b. Retail	($12)	($10)	($20)		($100)
2. CHARACTERISTICS					
a. % Energy Saved	33%	75%	50%		66%
b. Useful Life	10 years	3 years	20 years		20 years
c. Simple Payback Time (SPT)	2 years	1 year	2 years		1 year
3. UNIT LIFETIME SAVINGS					
a. Gross Energy	1330 kWh	440 kWh	10 MBtu		24,000 kWh
b. Gross $	$100 (2)	$33 (2)	$70 (2)		$1800
c. Net $ [3b-1a]	$92	$28	$60 (3)		$1700
d. Gross Equivalent Gallons (4)	100	40	80		1920
e. Miles in 25 mpg car	2500	1000	2000		48,000
4. SAVINGS 1985-1990					
a. 1990 Sales	3M	20M	20M		not
b. Sales 1985 through 1990	8M	50M	50M		ramping
c. Cum. Net Savings [4b x 3c]	$750 M	$1.4B	$3B	**$5B/5yr**	up
5. SAVINGS AT SATURATION					
a. U.S. Units	600M	750M	1400M		100M
b. U.S. Annual Sales	60M	250M	70M		6M
c. Annual Energy Savings [5b x 3a]	80 BkWh	110 BkWh	0.3 Mbod		144 BkWh
d. Annual Net $ Savings [5b x 3c](5)	$5.5B	$7B	$4B	**$16.5B/yr**	$10 B
e. Equivalent power plants (6)	16 "plants"	22 "plants"			29 "plants"
f. Equivalent offshore platforms(7)	45 "platforms"	60 "platforms"	30 "platforms"		78 "platforms"
g. Annual CO_2 savings(8)	55 Mt	80 Mt	18 Mt	**153 Mt**	100 Mt
6. PROJECT BENEFITS					
a. Advance in Commercialization	5 years	5 years	5 years		5 years
b. Net Project Savings [6a x 5d]	$27.5 B	$35B	$20B	**$82.5B**	$50 B
7. COST TO DOE FOR R&D	$3M	$0(9)	$3M	**$6M**	$2M
8. BENEFITS/ R&D COST [6b/7]	9000:1		6500:1	**14,000:1**	25,000:1

From: "The Role of Federal Research and Development in Advancing Energy Efficiency," Statement of Arthur H. Rosenfeld before James H. Scheuer, Chairman, Subcommittee on Environment, Committee on Science, Space, and Technology, U.S. House of Representatives, April 1991.

(1) Calculations for CFLs based on one 16-watt CFL replacing thirteen 60-watt incandescents, burning about 3300 hours/year, assuming that a CFL costs $9 wholesale, or $5 more than the wholesale cost of thirteen incandescents. For retail we take $18 - $8.

(2) Assuming price of 7.5¢/kWh for commercial sector electricity and a retail natural gas price of $7/MBtu (70¢/therm).

(3) For hot weather applications where low-e windows substantially reduce cooling loads, air conditioners in new buildings can be down-sized, saving more than the initial cost of the low-e window.

(4) Assuming marginal electricity comes from oil or gas at 11,600 BTU/kWh, thermally equivalent to 0.08 gallons of gasoline.

(5) Net annual savings are in 1990 dollars, uncorrected for growth in building stock, changes in real energy costs, or discounted future values. See Geller et al., Table 1.

(6) One 1000 MW baseload power plant supplying about 5 BkWh/year.

(7) One offshore oil platform = 10,000 bod. To convert "plants" burning natural gas to "platforms": 1 "plant" = 27,000 bod = 2.7 "platforms." Alaska National Wildlife Refuge, at 0.3 Mbod, is equivalent to about 30 "platforms."

(8) 1989 U.S. emissions of CO_2 were 5000 Mt.

(9) Descended from high-frequency ballasts (only DOE assistance was in testing).

discharge column, the conversion of plasma energy to ultraviolet is very efficient, but at each end there are voltage drops (anode and cathode "falls") adding up to about 15 volts, as ions and electrons drift into the electrodes to produce heat and not light. By raising the exciting frequency from 60 Hz (core-coil ballast) to 20-50 kHz (electronic ballast), the ion and electron drift distances are greatly reduced, the 15 volt end losses drop to about 8 volts and the efficacy of a 4 foot lamp rises 10 to 15%. In addition, the electronic ballasts are themselves much more efficient than core-coil, so the system efficiency rises another 10%, for a total gain of about 25%. Specifically, the heat dissipations of ballasts which operate *pairs* of 40 watt lamps are as follows: an outmoded "standard" core-coil ballast is 16 watt (i.e. an additional 20%), an "efficient" core-coil ballast is down to 10 watts, and an electronic ballast is only 4 watts.[17, 18,19]

A further benefit of electronic ballasts are that they are easier to control electronically, permitting "daylighting," i.e. the practice of dimming lighting to save electricity when daylight is available. This raises the system efficiency of electronic ballasts, averaged over an entire floor of an office building, easily 30 to 40% above undimmed "standard" ballasts.

The energy-efficient electronic ballasts described above were developed through DOE-sponsored research at LBL in the late 1970s. Electronic ballasts are now commercially available for about $15 each wholesale and, over their 10 year lifetime, save 1330 kWh and $100 (See Table 4). These savings are equivalent to 100 gallons of gasoline, enough to drive 2500 miles in a 25 mpg car. Between 1985 and 1990, 8 million electronic ballasts were sold in the U.S. Based on the net lifetime savings of $85 per ballast, cumulative net lifetime savings for these 8 million ballasts is $680 million. It is expected that 600 million electronic ballasts, saving production of 80 BkWh, emissions of 55 Mt CO_2, and expenditures of $5.5 billion annually, will have been sold when market saturation is reached. The initial DOE project to develop electronic ballasts cost $3 million and is estimated to have advanced commercialization by 5 years, for a net project savings of $25 billion. This represents over an 8000:1 return on DOE's investment.

Compact Fluorescent Lamps (CFLs)

The economics of CFLs are shown in **Table 5**. An individual CFL rapidly pays for itself through reduced energy bills. For example, one 16-watt CFL replaces a series of about one dozen 60-watt incandescents since it burns 12 times longer than the incandescents. This CFL would save 440 kWh and about $33 in electricity costs over its 40 month life in a commercial building.

A modern, automated CFL production plant costs $7.5 million and can produce six million lamps annually, each of which will save 440 kWh over its service life, for a total savings of approximately 2.5 BkWh per year, equivalent to the sales of a 500 MW intermediate or baseload power plant that costs up to $1 billion to construct and $200 million per year to operate.

Within a decade CFLs will penetrate enough of the U.S. market to save over half of the 200 BkWh used annually by incandescents. As shown in Table 4, when CFLs have saturated the market they will save production of 110 BkWh, emissions of 80 Mt CO_2, and expenditures of $7 billion annually. DOE spent no R&D money on CFLs -- they descended directly from the development of electronic ballasts -- but because of the electronic ballasts, commercialization of CFLs was also advanced by 5 years for a net savings of $35 billion. Thus, DOE R&D expenditures of $3 million for electronic ballasts actually resulted in total savings from advancing commercialization of electronic ballasts and CFLs of $62.5 billion, an incredible 20,000:1 benefit-to-R&D-cost ratio.

Table 5. Economics of a 16-Watt Compact Fluorescent Lamp (CFL) Assuming 1 kWh Costs 7.5¢.

	Prices			
	Wholesale[1]		Retail	
	Low	High	Low	High
Price of 1 CFL	$7.00	$10.00	$9.00	$20.00[2]
Price of Initial Incandescent	$ .75	$ .75	$ .75	$ .75
Net First Cost of CFL	$6.25	$9.25	$8.25	$19.25
Monthly Savings Using CFL (Electricity Savings plus Avoided Incandescent Cost)	$1.06	$1.06	$1.06	$1.06
Simple Payback Time (months)[3]	6	9	8	18
Lamp Life (months)	40	40	40	40

<u>Assumptions</u>

- **CFL/Incandescent Ratio:** One 16-watt CFL replaces thirteen 60-watt incandescents. One CFL lasts approximately 10,000 hours; thirteen incandescents at 750 hours each last 9750 hours.

- **Lifetimes:** We estimate that the lifetime of approximately 10,000 hours is spread over 40 months at 250 hours/month for typical usage in a commercial or office space.

- **Monthly Electricity Savings:** Replacing a 60-watt incandescent with a 16-watt CFL saves 44 watts at the meter. Over its lifetime of 10,000 hours, the CFL saves 440 kWh. Using the average price of electricity of 7.5¢/kWh, the CFL saves 440 x 7.5¢ = $33.00. This results in a monthly savings of $ .83.

- **Monthly Avoided Incandescent Cost:** The initial incandescent costs $ .75 and the remaining 12 incandescents are calculated to cost $ .23/month (12 x $ .75 = $9.00 divided by 40 months).

---

1 "Wholesale" is included above because innovative methods are being used by some utilities to make CFLs available to customers at wholesale prices, allowing the customers to realize large savings.

2 For less developed countries, like India, exorbitant import fees make this cost $35.00.

3 Simple payback time (STP) is the interval needed to recoup the money invested in an energy-efficient technology through reduced energy bills. STP ignores discount rates.

Windows From a Physics Perspective

Heat losses and gains through windows are responsible for 25% of all heating and cooling requirements in U.S. buildings. The fossil fuel equivalent of the heat loss alone is the 1.8 million barrel per day (Mbod) output of the Alaskan pipeline, or of Kuwait before 1991. If we understand how windows work thermally, we can easily see how to save half or all of this 1.8 Mbod.

Heat flow is typically measured in watts per square meter (W/m^2) in SI (Systeme Internationale, a subset of metric) units, and if linear in temperature, is written:

$$q = U \Delta T = \frac{1}{R} \Delta T, \qquad (10)$$

where U is the conductance (W/m^2K) and R is the resistance (m^2K/W).

In the U.S., where the IP system (inch, pound, Btu, etc.) is used, U_{IP} is expressed in units of Btu/hr ft^2 °F. The conversion factors are: $U_{SI} = 5.68\ U_{IP}$, and $R_{SI} = R_{IP}/5.68\ R_{IP}$. As an example, 4-inch stud/fiberglass insulated walls are R-11, i.e. have $R_{IP} = 11$, and 9 inch ceiling insulation is R-19. Converted to SI, R-11 becomes $R_{SI} = 2\ \Omega$, using Ω as a shorthand for m^2K/W.

Figure 8 shows the heat leak between a warm indoor room at T_i (at right) and a cold outdoors at T_o (at left).[20] (The convention that indoors is at the right comes from a more complete description of a window, with the sun on the left, shining through the window from left to right.) Glass itself is a poor thermal insulator; 1/8" window glass typically has a resistance of only 4 milliohms. Glass is also nearly "black" to heat at room-temperature (T_o or T_i), i.e. its emissivity, ε, is 0.84, so that heat radiates easily from all glass surfaces. Thus, the thermal resistance of a window is determined almost entirely by the resistance of air and by Plank's constant, σ.

Radiation across a gap is given by:

$$q_{rad} = \frac{\sigma\,(T_2{}^4 - T_1{}^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}, \qquad (11)$$

where ε_1 and ε_2 are the emissivities shown in Figure 8. This is linearized by writing $T_2 = T_1 + \Delta T$ to get:

$$q_{rad} = \frac{3\sigma\,(T_1{}^3)\,\Delta T}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}, = \frac{\Delta T}{R_{rad}}. \qquad (12)$$

Setting $T_1 = 255$ K, we get:

$$R_{rad} = 0.2\ \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right). \qquad (13)$$

For uncoated glass, $\varepsilon_1 = \varepsilon_2 = 0.84$, and:

$$R_{rad}\,(\text{uncoated}) = 0.2\,(1.4) = 0.28, \qquad (14)$$

which is "worse" than the parallel R(conduction and convection) shown in Figure 8 as $Rc{+}c = 0.5\ \Omega$.

Low-Emissivity (Low-E) Windows

Low-E windows follow the thermos bottle approach by using a thin, metallic mirror on one of the gap surfaces. As we shall see below, there are many semiconductors (like tin oxide) which have a high enough electron density so as to act nearly like a mirror to heat (ε=0.1) but transmit visible light. The technology of depositing low emissivity films on plastic was perfected in a collaboration between LBL and Southwall Technologies, which trade-marked the nice term "heat mirror," leaving the rest of the industry to use the words "low-E."

If ε_1 or $\varepsilon_2 = 0.1$, equation (13) becomes:

$$R_{rad} = 0.2\ (10.2) = 2\Omega, \qquad (15)$$

which is now 4 times as good as Rc+c. By coating *both* surfaces one could achieve Rrad = 4 Ω, but it's better to put the extra expense into filling the air gap with a heavier gas. Gas conduction is proportional to $1/\sqrt{m}$, where m is the atomic number. Argon, for example, will raise the gap resistance by about 1/3rd. One chooses a monatomic gas to avoid the heat capacity associated with rotational states.

To complete our discussion of Figure 8 we must still address the heat transfer to the outer surface. From the room to the inner glass, we have labelled $R_i = 0.13\ \Omega$. For uncoated glass this heat transfer is about half radiative, half convective. Outdoors is windy, so conduction overwhelms radiation, and Figure 8 shows $R_o = 0.03\ \Omega$. Now we can calculate R for an air-filled, low-e window. From equation (15), $R_{rad} = 2$, which in parallel with Rc+c = 0.5 gives:

$$R_{gap} = \frac{2 \times {}^1/_2}{2 + {}^1/_2},\ = \frac{2}{5} = 0.4. \qquad (16)$$

Then:

$$R_{window} = R_{outer} + R_{gap},\ (\text{i.e. } R_{window} = 0.03 + 0.13 = 0.4 = 0.56\ \Omega),$$

and in IP units $R_w = 3.2\ \Omega_{IP}$, called "R-3.2." This is significantly better than single glazing ($R_{SI} = 0.16$, R_{IP}=1), but still poor compared to a 4 inch wall at $R_{IP} = 11$. An Argon fill adds about 30% to the total resistance of the window and is becoming standard with the major window manufacturers. The latest trend is to go to "triple glazing," by stretching two thin films of low-E plastic inside the gap. Triple glazing with gas fills produce "superwindows" with R_{IP} = 6 - 9 which is nearly as good as a stud wall. But a wall can only insulate, while a window admits solar heat during the day. The result is that superwindows are net energy gainers facing in any direction in any part of the U.S.

Economics of Low-E Windows

The economics of low-E windows are impressive: their payback time is only two years and they are rapidly saturating the market. As shown in Table 4, at saturation, 70 million one square meter low-E "windows" will be sold in the U.S. every year. The net annual savings from these windows will be $4 billion. In the past five years, 50 million of these windows were sold in the U.S.; they have already saved $3 billion in cumulative avoided energy bills. One of these low-E windows costs $10 wholesale (or $20 retail) more than a typical thermopane window, but saves 10 to 15 million Btu over its 20 to 30 year lifetime, worth approximately $70 in avoided energy bills.

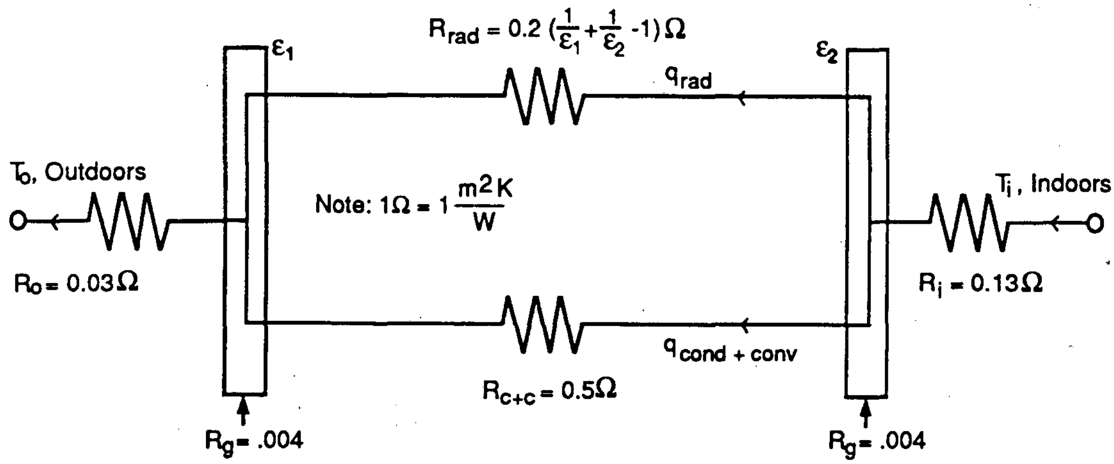


Figure 8. Thermal Circuit for a Double-Glazed Window.

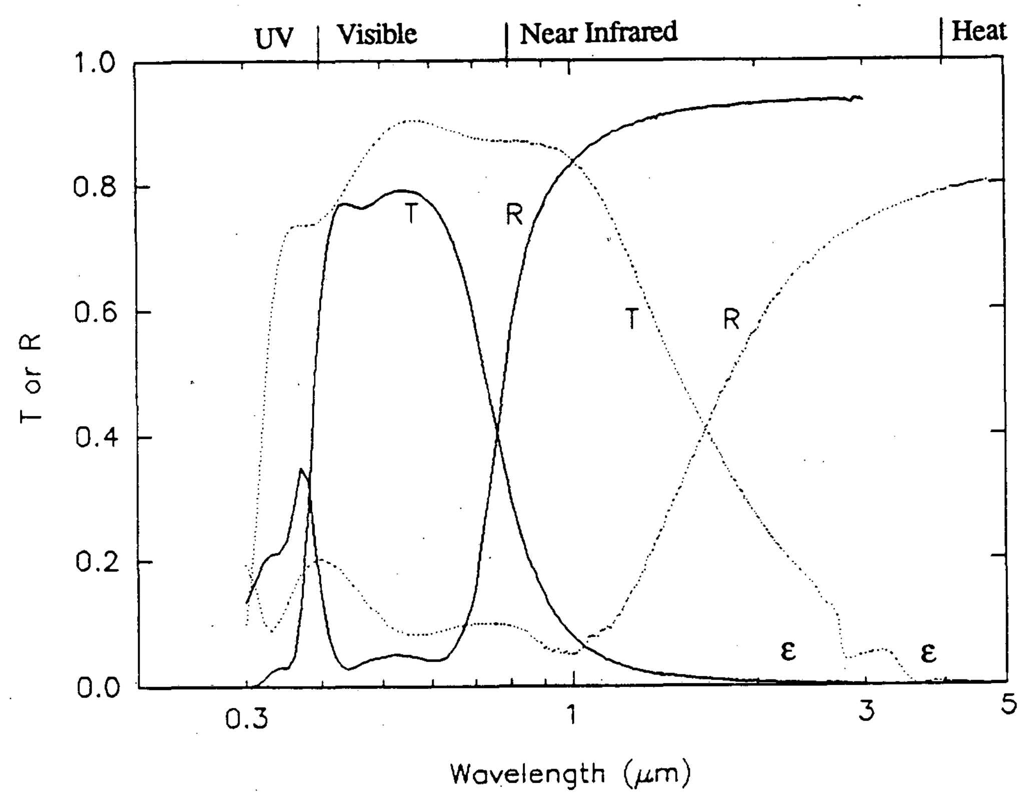


Figure 9. Transmittance (T or ε) and reflectance (R), for normal incidence, of two samples of coated glass. Dotted line: In_2O_3:Sn-coated glass manufactured by Donnelly Corporation, Holland, Michigan. Solid line: Multilayer-coated glass manufactured by Cardinal IG, Minneapolis, Minnesota 55426.

Spectrally Selective Windows - Plasma Frequency

The previous discussion focused on low-E coatings for cold weather, where all that was needed was for ε to be small (≤ 0.1) for "heat" (with wavelength $\lambda > 5\ \mu$), but approach 1.0 for light ($\lambda < 0.8\mu$). But windows can also be made spectrally selective, creating the opportunity to use them more effectively in hot climates. The energy in sunlight is about half visible ($\lambda < 0.8\mu$) and about half in visible near-infrared heat. In winter, this near-infrared is welcome, but in hot weather it must be reflected along with the far infrared. To "take the heat out of sunlight" [21] the transition in ε must be moved very close to 0.8μ as shown in **Figure 9.**[22] Not only does this save air conditioning bills, but it also reduces the first cost of a new building because the designer can down-size expensive chillers.[23] A visually transparent but selective window is more more desirable than the conventional reflective "solar control" glazing used universally on commercial buildings because they do not darken the interior space and thus avoid the need for artificial lighting even near the windows.

Also, in hot climates vernacular architecture often relies on vertical and horizontal overhangs to block incoming sunlight to reduce solar gains and air conditioning needs. Because spectrally selective windows solve the problem of solar heat gains, these overhangs are no longer essential and greater application of daylighting principles is possible. Daylighting saves even more electricity by reducing demand for lighting. In fact, the effect of using spectrally selective windows in hot climates is so dramatic that it calls for a new "least cost" approach to building design that adequately addresses these interactions.[24]

The basic physical idea behind a low-E or spectrally selective coating is the optical response of conduction electrons in a semiconductor or metal. This can be approximated by the dielectric function :

$$\varepsilon(\omega) = \varepsilon_\infty \left[1 - \left(\frac{\omega_p}{\omega}\right)^2\right] = (\tilde{n})^2 \qquad (17)$$

where $\tilde{n}$ is the index of refraction which governs wave propagation.[25] For frequency ω greater than the plasma frequency ω_p, ε is positive, the refractive index $\tilde{n}$ is real, and waves can propagate in the material. For $\omega < \omega_p$, $\varepsilon < 0$, the refractive index is imaginary, so a wave incident on the material is reflected.

The most familiar example of this transition is the difference in propagation of electromagnetic waves in the ionosphere. Low-frequency radio has $\omega < \omega_p$, and $\tilde{n}$ is imaginary, so the waves are reflected and will bounce between the earth's surface and the ionosphere, all around the world. Short-waves (fm band, tv, and microwave) have $\tilde{n}$ real, easily penetrate the ionization, and are lost; hence to receive these high frequencies, we have to be within line of sight of the transmitter.

The plasma frequency ω_p depends on the conduction electron concentration n through:

$$\omega_p^2 = \frac{4\pi n e^2}{m\varepsilon_\infty} \qquad (18)$$

Here e is the electronic charge, m is the effective mass, and ε_∞ is the background dielectric constant from the bound charges. In a metal, n is typically 10^{22}cm^{-3}, and ω_p falls in the ultraviolet. In a heavily-doped semiconductor, n can now be 10^{20} to 10^{21}cm^{-3}, with ω_p in the near-infrared. This is shown for a tin-doped indium oxide coating in Figure 9. The reflectance changes over a range of a few μm near the plasma frequency due to scattering and trapping of the electrons.

For a sharper roll-off and better spectral selectivity, multi-layer coatings are used. One layer is a very thin (~ 10nm) metal film, often Ag. In this case ω_p is in the ultraviolet, but the magnitude of ε changes fairly slowly near ω_p. As a result, for a thin metal film alone, the reflectance changes slowly from nearly 0 in the ultraviolet to nearly 1 in the near-infrared. When the metal film is sandwiched between dielectric layers, thin-film interference effects can sharpen the transition from high transmittance to high reflectance. A five-layer coating can give a close approximation to a step at the visible-near infrared boundary, as illustrated in Figure 9.

Appliance Standards

Along with R&D funding, legislatively-enacted standards also perform the function of advancing technology development. An example of the benefits of such standards in improving the energy efficiency of appliances is provided in the last column of Table 4. This column illustrates the energy and economic savings attributable to the 1985 California refrigerator and freezer appliance standards when compared to 1976 base case appliances. Manufacturers complied nationwide with the California standards; annual energy saving are now over 140 BkWh, valued at $10 billion and equivalent to the electricity produced by 29 baseload (1000 MW) power plants.

In many cases, appliance standards are the easiest way to remove or discourage inefficient products from the market. A recent study compared various policy options and found that standards result in more savings than other methods, including tax credits, rebates, and consumer education.[26] Currently, the Federal government has set energy efficiency standards for many home appliances and fluorescent ballasts. Significant additional energy and CO_2 savings may be achieved by standards for other products such as motors, lamps and lighting fixtures, office equipment, windows, and commercial HVAC equipment.

Building Energy Performance Standards

Performance standards for new buildings have yielded amazing results.[27] In 1975, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) announced its ASHRAE 90 series of voluntary standards. By 1978 California had adopted tougher mandatory standards that have about 3-year payback times and which are enforced. Most states have adopted the ASHRAE standards, but enforcement is inconsistent, with notable offenders being the federal government and some state governments.

The savings are remarkable. In 1975 a typical new office tower annually consumed 170 kBtu of natural gas and 30 kWh of electricity per square foot. This consumption has now dropped to 10 kBtu (a savings of 95%) and 10 kWh (a savings of 2/3rds) and the buildings are better designed and more comfortable. The California Energy Commission estimates that annual savings from new California buildings alone will reach $1 billion by 1995, so we can significantly spur the U.S. economy by updating and enforcing standards in all states and for federal buildings.

LATEST DEVELOPMENTS AND DIRECTIONS FOR FURTHER ENERGY EFFICIENCY EFFORTS

Advanced Windows

As discussed above, a new generation of "superwindows," rated from R-6 to R-10, is advancing the performance of windows even farther. Superwindows increase a window's performance from R-4 to R-8 by stretching two plastic films with low-E coatings between the double glazing of an R-4 window and filling the air gaps with argon or krypton. When the window frame is also improved, the advanced window's performance is increased to R-8. In field tests, superwindows outperform 6-inch thick R-19 walls because they let sunlight into the building during the day and block heat loss to the outdoors at night. The superwindow is a net energy gainer, whereas the surrounding wall only prevents heat loss.[28] In addition, superwindows minimize interior condensation and reduce the damage to furnishings by blocking ultraviolet rays. Although these windows can cost 20% to 50% more than conventional windows, their initial cost is repaid in about four years of avoided energy bills.

Electrochromic windows that control the flow of radiation are now under development. These windows switch from clear to white under electronic or thermal control. Initially, these windows will appear in automobile applications, but eventually the new windows will penetrate the buildings market.

Advanced Insulation

Optimum U.S. homes have walls with 6 inches of insulation (R-19) contained within an outer insulating sheath (for a total of R-24) in contrast to standard homes which use only a scant 4 inches of insulation (R-11). Some builders, such as Bigelow Homes in Chicago, have so much confidence in the performance of optimum and super-insulated residences that they offer to pay all owners' annual energy bills that exceed $100 for townhouses and $200 for private homes. In 1989, the contest for the homeowner with the lowest heating bill was won by a customer who paid only $24 for heating for an entire year.

Concern over both ozone depletion and global warming has led to regulations banning the manufacture of chlorofluorocarbons (CFCs), whose most widely recognized use is as a refrigerant. Less well known is the fact that a typical U.S. refrigerator contains about 1/2 lb. of CFCs in the compressor, and twice that much in the CFC-blown highly-insulating foam that fills the shell of the box. Hence, there are now many parallel R&D efforts underway to replace this foam.

At least four kinds of advanced super-insulation are currently being developed with the support of the Department of Energy. One form of superinsulation is an outgrowth of advances in low-E window technology. Gas-filled panels (GFPs), which have been developed specifically in response to the need to replace CFC blown foam insulation, are an assembly of reflective foils that simultaneously minimize radiative, conductive, and convective heat transfer. Multiple layers of highly reflective metallized polymer film compartmentalize the interiors of the GFPs, virtually eliminating radiative heat transfer. Much thinner, crumpled film is inserted between these parallel layers to minimize convection and further decrease radiative heat transfer. In addition, to reduce conduction, a low thermal conductivity gas (such as argon or krypton), or gas mixture, is encapsulated at atmospheric pressure within sealed panels. These GFPs may someday be applied in HVAC insulation, hot water heaters, swimming pool and spa covers, refrigerated transport walls, airplane bodies and even homes. Compared with fiberglass at R-3.5 per inch, GFPs have tested at R-7 to R-13 per inch, and an R-15 performance is anticipated.[29]

"Aerogel" is a transparent or translucent insulating material also developed at LBL. Aerogel can be used in windows and skylights as well as in appliances. In its opaque, evacuated form, it has reached R-30 per inch.

Low-Flow Showerheads

The typical showerhead flows at 5 gallons per minute (gpm) and the typical shower is 5 minutes long. (The showerhead industry claims that normal showerheads use 6 to 10 gpm. A recent study conducted in Yakima, Washington found that the average showerhead used 3.1 gpm.[30]) The fuel required for heating the water from 55°F to 110°F is 600 Btu/gallon; annually, this is the equivalent of 44 gallons of oil. The annual cost of natural gas for this typical shower is $32.

Low-flow showerheads use 2.5 gpm, half the amount of conventional showerheads, so they save $16/year, with a present value (20 years, 6% real interest) of nearly $200. Based on initial costs for a replacement showerhead of between $5 and $10, simple payback times are well under a year.

Extrapolating to the entire U.S., these water- and energy-conserving showerheads will reduce annual U.S. fuel consumption from the equivalent of 0.3 million barrels of oil per day (MBod) to 0.6 MBod, equivalent to the expected oil production rate from the Alaskan National Wildlife Refuge.

Improving Recessed Lamp Fixtures

In U.S. commercial buildings there are about 300 million recessed fixtures for incandescent lamps. The advantages of replacing incandescent lamps with compact fluorescents have been discussed above. But a problem remains: 100-200 million of the incandescent fixtures are still equipped with all-too-familiar black "microgroove" collars that were initially designed to keep a bright filament out of sight. Such an absorber allows omni-directional light to escape only downward in a 45 degree cone, and necessarily absorbs three-quarters of that light. Thus, if the lamp is 60 watts, the black collar probably absorbs about 40 watts. If the lamp burns 3000 hours per year, the collar absorbs 120 kWh, worth about $10 per year. Multiplied by 100-200 million, the annual cost of this wasteful technology is $1-2 billion per year.

These collars persist even though the direct view of a filament disappeared in the 1940s, because lighting designers still emphasize style over energy costs. If designers were trained in energy efficiency, 3 to 4 baseload power plants would be liberated from generating the light and heat absorbed by such fixtures.

Whitening Surfaces and Planting Urban Trees

Most U.S. cities are 3 to 6 degrees Fahrenheit (°F) hotter on summer afternoons than they were 50 years ago. These summer "urban heat-islands" arise because heat-absorbing asphalt and buildings have replaced trees and fields. Downtown Los Angeles is 7 °F hotter than in 1940, and is heating up by 1 °F every 8 years.

An unshaded U.S. home with a dark or terra-cotta colored roof typically needs 2 to 3 kilowatts (kWs) for air-conditioning. This costs the average homeowner between $100 and $300 annually. In contrast, a shaded home with a light-colored exterior generally uses only half this amount of electricity.

Such simple, low-technology mitigation measures as planting urban shade trees and whitening surfaces of roofs, streets, and sidewalks can garner tremendous savings when their impact is aggregated for an entire city, state, or region. In Los Angeles alone $100,000 per hour in peak summer air-conditioning costs would be saved.[31] Lowering temperatures in urban heat islands by 5 °F could save U.S. rate payers about $1 billion per year in avoided air-conditioning. And since smog "cooks" slower at reduced temperatures, eliminating heat islands would significantly lower levels of smog. Of course, such temperature reductions would also reduce (by 1/2%) the power plant CO_2 emissions associated with generating electricity.

Daylighting

Designing buildings that maximize sunlight to illuminate interiors is a low-technology approach to reducing building energy demand while meeting building lighting needs. This practice is widespread in Europe, where every office has an outside window, but is still under-utilized in the U.S. Just one square foot of direct sunlight can actually illuminate 200 square feet of interior space, if evenly distributed through a skylight or clerestory window.[32]

Thermal Energy Storage

In a well-insulated building with low-E, well-managed windows, thermal storage can economically save most of the energy now used for heating and cooling. For example, a super-insulated home with exposed masonry floors and perhaps with a south-facing "Trombe" wall will hold heat for days. If its windows are concentrated towards the south, and are well-managed, it can get through the winter comfortably on the free heat from sun, appliances, and occupants, plus space heat corresponding to about 1 Btu/ft^2/degree day (°F) compared with 8 Btu for a typical pre-1975 U.S. home, or 4-5 Btu for newer homes. Also, in most of the U.S., the same super-insulated home, with a white roof, well-managed windows, and a whole-house fan to draw in cool night air, can remain comfortable all day with no air-conditioning or with one or two small window units.

The same thermal energy storage techniques apply to offices, where in fact there is more free heat than in homes. In Sweden, a modern office building is designed to store free heat during a winter week, cool slightly over the weekend, and use the stored heat to warm itself up on Monday morning. Accordingly, many offices no longer request a connection to the Stockholm district heating system. Similar strategies of night cooling are used during the summer, and greatly reduce the demand for peak power.[33]

CONCLUSION

Numerous studies show that energy-efficient technologies and strategies such as these can save an incredible amount of energy and slow the annual growth in CO_2 emissions that contribute to global warming. Even more impressive, these important environmental savings can be realized at a net economic benefit. Adequate R&D funding is imperative to continue to develop technologies and strategies to capture these savings. Then, effective energy efficiency policies that promote widespread technology transfer and implementation are essential.

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