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RESIDENTIAL ENERGY EFFICIENCY:
PROGRESS SINCE 1973 AND FUTURE POTENTIAL

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RESIDENTIAL ENERGY EFFICIENCY:
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ABSTRACT

Today's 85 million U.S. homes use $100 billion of fuel and electricity ($1150/home). If their energy intensity (resource energy/ft^2) were still frozen at 1973 levels, they would use 18% more. With well-insulated houses, need for space heat is vanishing. Superinsulated Saskatchewan homes spend annually only $270 for space heat, $150 for water heat, and $400 for appliances, yet they cost only $2000 ± $1000 more than conventional new homes.

The concept of Cost of Conserved Energy (CCE) is used to rank conservation technologies for existing and new homes and appliances, and to develop supply curves of conserved energy and a least cost scenario. Calculations are calibrated with the BECA and other data bases. By limiting investments in efficiency to those whose CCE is less than current fuel and electricity prices, the potential residential plus commercial energy use in 2000 AD drops to half of that estimated by DOE, and the number of power plants needed drops by 200.

For the whole buildings sector, potential savings by 2000 are 8 Mbod (worth $50B/year), at an average CCE of $10/barrel.

I. INTRODUCTION

In 1984, U.S. buildings used about $165 B (billion) of energy (38% of the U.S. total costs) of which about half was "wasted." By "wasted" I don't want to invoke the first or second laws of thermodynamics, I only mean that if for the next 20 years we were to follow a "least-cost" investment scenario (optimizing our investment in efficient use vs. new supply), the buildings sector would emerge using only abut half as much energy as is projected today by most economists and policymakers.

Although its energy use is huge and wasteful, the buildings industry is badly fragmented and supports very little research and development. Since 1973, many physicists have switched their research from more traditional fields to building science and are proud of their contributions to spectacular gains in efficiency. I think there is a need for even more of us to be doing such rewarding research and development. Right now, under the Reagan Administration, federal and state support has dropped sharply, but I still assert that any field which has a potential annual savings of $85 B [see Note a] is bound to support increasing R&D. In other words, conservation is not a transient slogan; it has grown to be a profession, it will be with us henceforth.

Table I and *Fig. 1* show the importance of buildings in the U.S. economy. In 1984, our buildings sector used $165 Billion worth of energy, mainly (60%) as electricity. In fact, of the total annual U.S. electricity sales of $135 Billion, most ($100 B or 75%) went to the equipment and appliances in buildings.

In 1984, 236 million Americans spent, per capita, $1800 for energy, of which $700 went into buildings and their appliances and equipment. The average home pays $1150 of annual bills for 2.8 people. Based on Table I we can make the following remarks about the building sector. Of the national costs for buildings; $165 B, 60% goes to residences and 40% to non-residential (called "commercial") buildings; 60% of the $165 B for buildings goes for electricity (accounting for 75% of all the $135 B of electric revenues). It's not a bad approximation to say that the past and the future of the electric industry depends on trends in the buildings sector. Thus in *Fig. 3* (below), you'll note that our least-cost scenario[1] frees 200 standard plants to serve more productive uses or even not be built. This 1980 estimate was based on whatever technology was already on the market; it did not count on any of the dramatic improvements in lighting or daylighting discussed elsewhere in this book.

Table I. 1984 U.S. Energy Expenses

	Fuel ($B)	Electricity ($B)	Total ($B)
Buildings Sector	65	100	165
Residential	(45)	(55)	(100)
Commercial	(20)	(45)	(65)
Industry	70	35	105
Transport	160	0	160
Total	295	135	430

To get a better feeling for the cost of energy in buildings, we note that the U.S. has 85 M occupied dwellings, with a total floorspace of about 110 B ft^2, and another 50 B ft^2 of non-residential ("commercial") space. So every square foot costs about $1/year in energy services, with residential space costing $0.90 and commercial space costing $1.30, while the energy for new office space costs $0.50 to $1.00.

Because of rising prices and enhanced awareness during the period 1970-84, the energy/GNP ratio for the entire economy dropped to 73.5% of its former value. If our energy efficiency were still frozen at 1970 levels,

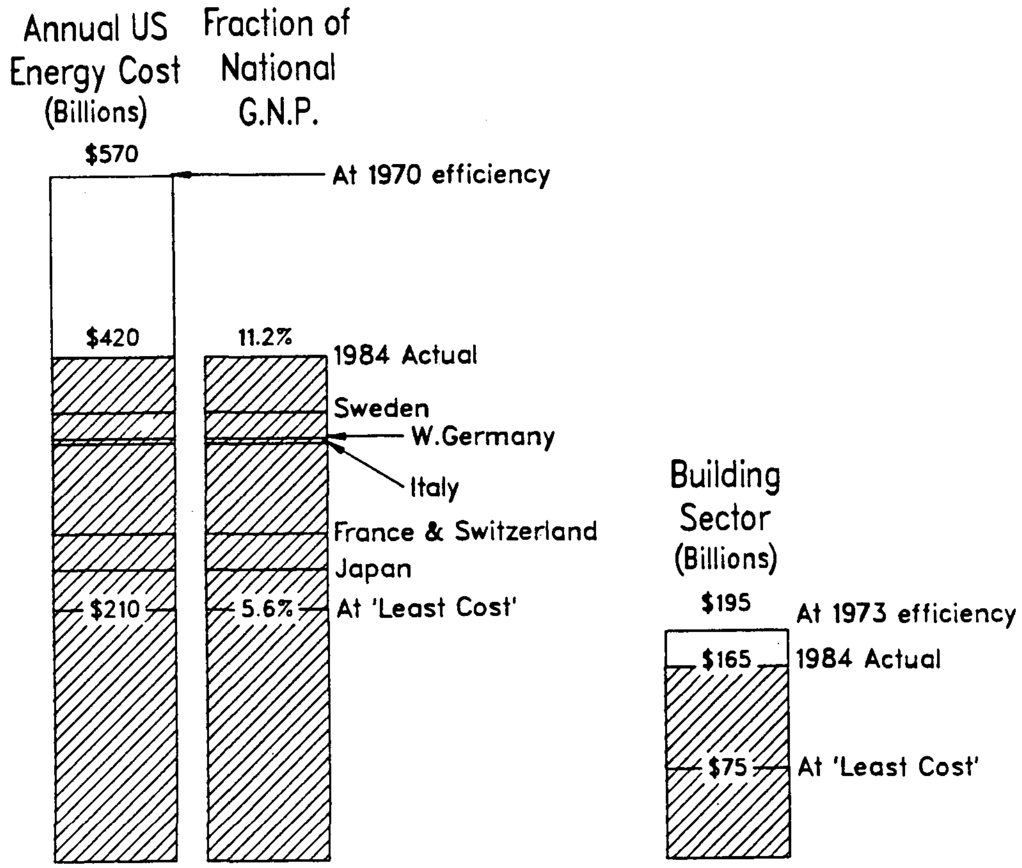

Fig. 1. Annual U.S. Energy Cost, from Table 1.
(a) Energy use per $ of GNP (in constant $) has dropped to 74% from 1970 to 1984; if efficiencies had stayed frozen at 1970 values, our $420 B annual costs today would instead be $420 B/0.74 = $570 B. On right bar, "Fraction of National G.N.P.", are lines (from "Btu Plot" figure 4) representing 1984 fractions for European countries and Japan. These lines extended left to the U.S. bar show what the 1984 U.S. economy would pay for energy at foreign efficiences. Source: DOE/EIA-0376 (85).

we would today be paying $420 B/0.735 = $570 billion annually, i.e., we are actually saving $150 billion, ($570 B - $420 B) each year, a very significant sum which is comparable to our highly publicized national deficit.

In buildings, the percentage savings are comparable. In the last decade, we have built 27% more homes and added 32% to our commercial floor space; yet primary energy use in buildings is up only 10%; so the energy/ft^2 is down to 85% (1.10/1.29) of its former value, and we are actually saving $30 B/year.

That brings us to trends in homes and to *Fig. 2*, we just mentioned an energy bill per home of $1200; the left part of Fig. 2 shows how it is distributed between space heat (50%), appliances (35%), and water heat (15%). (To get the total cost of $1200 from the costs/ft^2 of Table I and Fig. 2, remember that the average existing single- family home has a floor area of 1320 ft^2.)

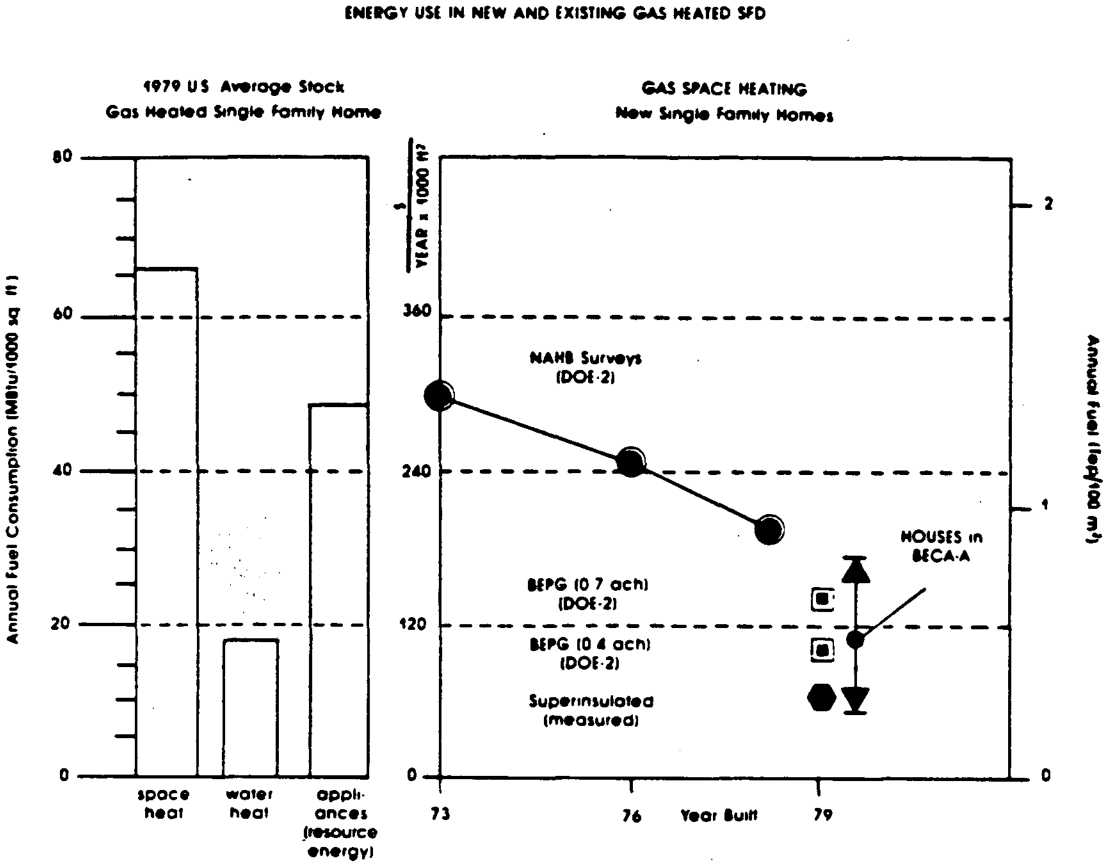

Fig. 2. Energy Use in New and Existing Gas Heated Single Family Houses.
The bar graph shows average space heat and appliance energy use for the 1979 stock of gas heated single family homes. Space heat and hot water use were calculated from NIECS utility billing data (Meyers, 1982). Appliance use is based on unit consumption and appliance saturations used in the ORNL model and includes electric appliances, such as refrigerators and lighting (air-conditioners are excluded), with electricity counted in resource energy units, using 1 kWh = 11,500 Btu. The points labeled "NAHB" are DOE-2 computer simulations of space heating in homes built by builders surveyed by the National Association of Home Builders in 1973, 1976, and 1979. The simulations were normalized to the Washington D.C. climate, which has approximately the same number of degree-days as average new building stock. Because of the non-random nature of the NAHB survey, results cannot be extrapolated to all new homes. Furthermore, The assumptions used in the simulation may not accurately represent lifestyle or building characteristics, however, they serve here as an example of energy use in new homes now on the market. "BEPG" represents proposed federal energy guidelines for practice that more closely approaches minimum life-cycle costs, using the same assumptions about thermostat settings, furnace efficiency, and free heat as the NAHB points. "Superinsulated" is the average of the 15 best-performing superinsulated houses of 30 for which detailed data were available in Ribot et al., 1982. It represents measured energy use, normalized to average degree-days for new buildings, using assumptions comparable to the NAHB and BEPG point. Source: Rosenfeld/Wagner (1983)-Labels. XBL 856-2816

The right part of Fig. 2 deals with new homes; it shows the impact of rising fuel prices--builders learn to build and sell more efficient homes, and the heating needs of new homes fell 25% in 6 years. Plotted in 1979, we see four interesting cases:

1. average homes built by NAHB members, which were heated for $250/year per 1320 ft^2 home.
2. Building Energy Performance Guideline (BEPG) "optimized" home, but without mechanical ventilation ("mv.") (unwise), $170/year.
3. BEPG optimized home, with mv., and heat recuperation ("hr.") (wiser), $120/year. (Mv. and hr. are discussed by Fisk elsewhere in this book.)
4. superinsulated homes, again with mv. and hr., heated for $100/year (for 2300 heating ^{o}C-days), which we shall now discuss (wisest).

o Superinsulated Homes

Superinsulated homes are becoming popular in the northern U.S. and in Canada. They typically have at least "R-20" wall insulation and "R-40" ceilings, and have an average space heat requirement of approximately 5 kW for a ΔT (outdoor - indoor) of 30^{o}C [Note b]. The heating system needs such a small capacity (10 kW for the coldest days) that it is often combined with the domestic water heater whose rating is also about 10 kW. Superinsulated Saskatchewan homes, using natural gas heat, have typical heat bills of around $250--small compared with $550 for hot water plus appliances (which, in fact, provide much of the yearly heat). In Saskatoon recently, one-quarter to one-half of new homes are superinsulated (the fraction varies along with changes in the Canadian incentive programs and the economy). These homes take advantage of passive solar gain by mildly concentrating their windows towards the south, but they need not have large windows, so they look more "conventional" than "passive."

Before we leave this topic, I should try to explain as best I can why superinsulated homes fall below the BEPG "economic optimum" point in Fig. 2. Part of the explanation is a difference in the definition of "optimum." The square labelled BEPG (0.4 ach) was calculated using the DOE-2 computer program, but the economics failed to include the dollar savings available as the furnace is downsized or eliminated. Builders of superinsulated homes, of course, consider (indeed, aim for) these savings. A second part of the explanation is that occupants of superinsulated homes probably operate them very carefully and efficiently. A third part is that these homes may indeed be slightly over-optimally insulated and glazed, but it doesn't appear to be a very serious over-investment; the homes typically cost $2000 ± $1000 above conventional practice (with a very long high cost tail). See Fig. 14 below.

o Integrated Appliances

In the winter there are two recuperable leaks of heat from the home--the exhaust air and the used ("grey") water. In the colder parts of the U.S., it pays to recuperate at least one of these two. A superinsulated house has a very short heating season (only the few months when the outside temperature is below about 55°F). Above 55°F outdoors, one still has to keep the windows closed, but the appliances and the sun supply enough heat, and one needs no auxiliary space heat. In that case, one should start putting the excess heat from the refrigerator and the exhaust air into the hot water tank. By summertime, one should add the waste heat from the air conditioner. So, of course, by the turn of the century we can expect to see many integrated appliances, combined in a central utility core and controlled by a microprocessor.

o More Efficient Appliances

If we have good information, labelling, incentive, and loan programs, Americans will pay more attention to life-cycle cost when purchasing appliances. In that case, the overall[2] potential saved operating expense is about 40%, but refrigerators, freezers, and lighting can each drop about 50%. In Section II, Fig. 7 will show a complete "supply curve" for electrical appliances.

o More Efficient Lighting

With the introduction of high-frequency ballasts for fluorescent lamps (see Berman's chapter), their energy use in homes will drop about 25% (and by 40% in offices, where they can cheaply capture the added savings from daylighting). With the introduction of small screw-in fluorescent bulbs to replace incandescents, the residential lighting bill will decrease to one half. In the next 10-15 years, as these two remarkable devices replace today's ballasts and lamps, they will together save about 200 BkWh, worth $15 Billion/year and corresponding to the output of 40 standard 1000-MW power plants (200 BkWh is 60% of the 325 BkWh sales in 1984 by our entire stock of nuclear plants).

o Halving the Energy for Heating Water

Even without integrated appliances, the energy needed to heat hot water can decrease to about 60% as appliances are redesigned to use less hot water, people learn about cold-water laundry soap, and hot water heaters use solar preheat or heat pumps. [Ref. 1, Fig. 1.36]

o Indoor Air Quality

Before the 1973 oil embargo, we were beginning to be concerned with smog and soot and outdoor air quality in general, but never dreamed that indoor air quality was an even more pressing environmental problem. Nobody pointed out that indoor air is mainly outdoor air with some added pollutants, or pointed out that we spend most of our time indoors. Starting about 1974, and before inaugurating programs to "tighten" homes, i.e., reduce their infiltration rate below the typical 3/4 to 1 "ach" (air changes per hour), building scientists did have the wisdom to measure indoor air quality, so as to determine a "safe" number of ach. We then learned two things which may appear contradictory the first time you hear them.

1) It is safe to reduce the infiltration rate about in half the homes in the U.S.

2) Radon in U.S. homes causes about 10,000 lung cancers per year (within an uncertainty factor of 2-3). Over one-half of these cancers are caused in a relatively small number (about 10%) of homes. Clearly in these homes the need is not to reduce the infiltration rate but to remove the source of radon. The unit of radioactivity for radon (1 pCi/litre) can be equated with the risk of smoking about 1/2 cigarette/day (when the windows are closed, mainly during the winter). About 2500 of 10,000 total lung cancers per year may come from the worst few percent (about 3%) of our homes. Therefore, clearly, in many parts of the U.S., new homes will have to be monitored for radon and other indoor pollutants. [See Sextro's Chapter.]

o Load Levelling

Today, because of air conditioning, most U.S. utilities experience their peak power demand on hot afternoons. The cheapest (non-hydro) new peak power is generated by a gas turbine, which costs about $1000/kW of capacity, and burns expensive kerosene. (The $1000 includes transmission and distribution.) Thus a 100-W lamp burning on a summer afternoon requires a utility investment of $100! Or an uninsulated, uncovered water bed (150 Watt average) requires an investment of $150, even though insulation and a quilt will cut its losses to 50 W and cost far less. And an electric hot water heater (diversified afternoon load of 350 W) costs a utility $350. These examples explain why homes must soon have time-of-day meters and why these smart meters must control appliances. A brilliant example of this is the British Credit and Load Management System ("CALMS"), which listens by radio to a new price of electricity every 5 minutes, as broadcast by a BBC sideband. For $200 of hardware, CALMS turns the home into nine different "interruptible" circuits, controls appliances, performs as a clock thermostat, and does other clever things [see chapter by Bulleit and Peddie].

o Home Energy Ratings and Labels

One of the reasons that homes have not responded to the energy crisis as fast as autos or commercial buildings is that homes have not had "mile per gallon" stickers, and (unlike the buyer of a car or an office building) the purchaser of a home is usually unable to predict his energy bills. Today we know enough to rate homes to an accuracy of $50-100/yr.[2], and labels are being introduced in the U.S. and Western Europe. The impact of ratings is amplified because U.S. wholesale lenders ("Freddie Mac" and "Fannie Mae") are now willing to offer bigger and better loans on energy-efficient homes.

o Existing Homes and Commercial Buildings

In the discussion above, I have tried to give an impression of the new "turn-of-the-century home" and to show that there is room for physical and engineering innovation. Many of the improved appliances and controls will, of course, also be installed in existing homes. As for new commercial buildings, the changes are even more striking--many modern office blocks in Sweden get through the winter entirely on heat from the lights and occupants; in fact, they heat up during a winter day and use their thermal mass to coast over nights and weekends. Modern office buildings in warm climates like Reno, Nevada, can store enough "coolth" from the night air to get along without conventional air conditioning, and even in soggier climates, air conditioning (which amounts to about 40% of all our peak power) can (with the help of thermal storage) be shifted ahead to the previous night, when power is cheaper and cooling towers are more efficient.

In this introduction, I have tried to interest you enough to induce you to put up with Section II, which discusses Least Cost Studies and the cost of conserved energy; this section has more economics and methodology and less physics. Section III will discuss results from the residential sector.

II. LEAST COST STUDIES AND CONSERVATION "SUPPLY CURVES"

The Potential, in Buildings, for Saving 8 Mbod by 2000 AD, at a Cost of $10 Per Conserved Barrel

I will focus on the conclusions of the Buildings Panel from the SERI Solar/Conservation Study[1] (of which I was chairman). In Section A., I will summarize the conclusions; in Section B., I will define "cost of conserved energy," "supply curves of conserved energy," and then "conservation potentials". I will discuss commercial buildings in another chapter in this book.

A. Summary of Results

To whet your appetite, before stopping to define the method, I present *Fig. 3* which shows the potential for both fuel and electric use for the buildings sector to drop to half of conventional wisdom, by 2000 AD--a savings of 8 Mbod [Note c].

Let's discuss first Fig. 3(a): "Fuel". Two "Base Cases" were shown; they are the 1978 and 1979 medium- price, medium-growth projections from DOE's 1978 Annual Report to the Congress. Dropping faster than the base case is our Potential, made up of a decreasing white bottom area (existing buildings) and a small but growing shaded top (new buildings). The white bottom falls mainly because existing buildings can be retrofit; in addition, 20% of them will be demolished by 2000 AD. The grey wedge is small because new homes tend increasingly to be superinsulated and so to use very little heat, and new commercial buildings to use none. The "Low Renewable" line assumes that most homes install solar domestic hot water by 2000, and most new homes gain some passive solar heat. The "High Renewable" goes a bit further out the supply curve for solar options than we did for conventional options, only because we had more data for solar products.

Figure 3(b): Electricity. Unlike fuel use, where the base case is falling, conventional wisdom forecasts annual electric growth at 2.3% (compounding to 60% by 2000 AD). By contrast, the SERI study saw a potential drop to 3/4 of present use (at about 1% per year) despite an 80% growth in GNP by 2000. The

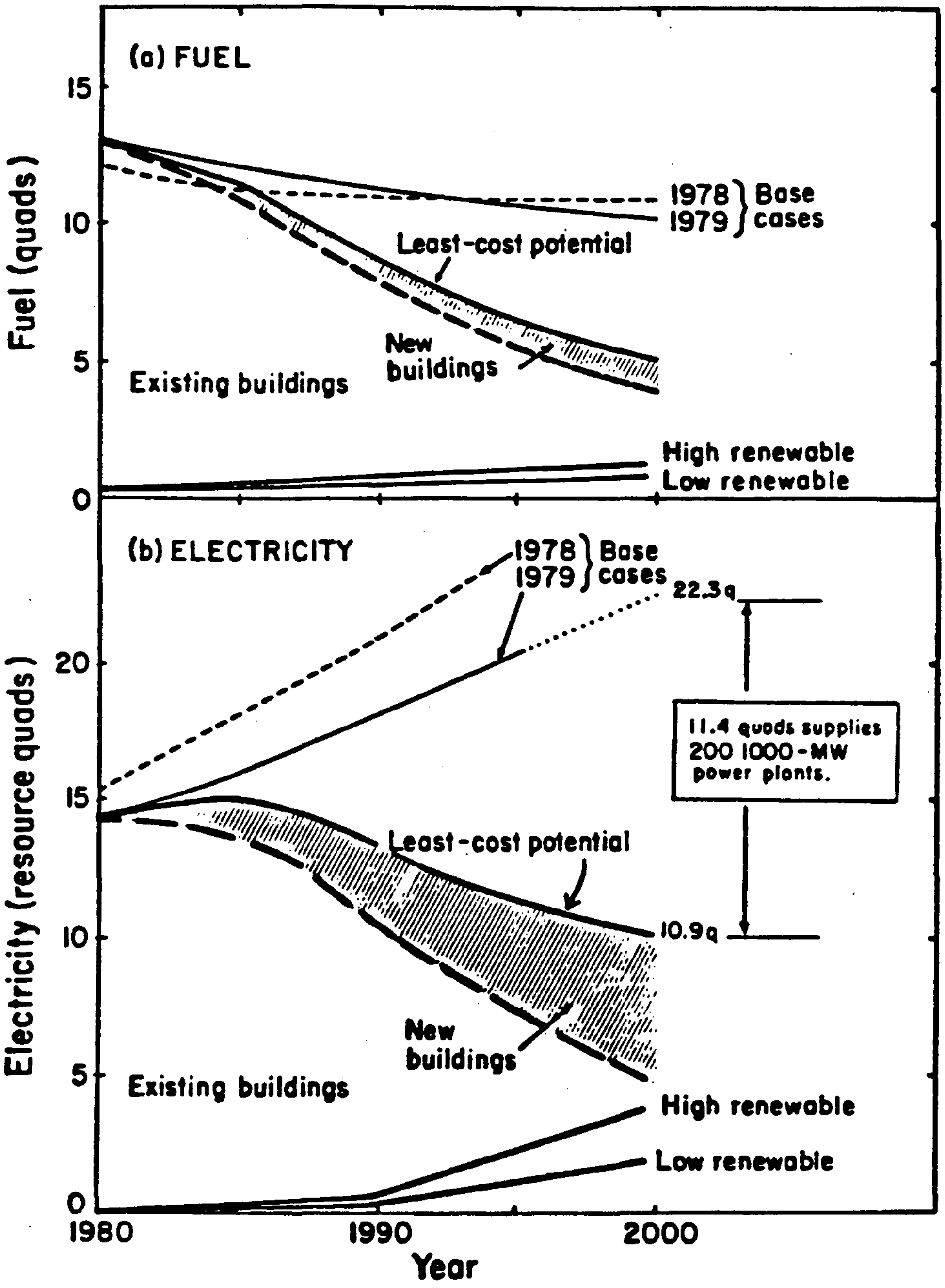

Fig. 3. Potential for saving half of fuel and half of electricity by 2000 AD, from the Building Chapter of SERI Solar/Conservation Study [A New Prosperity (1981)]. Base cases are from 1978 and 1979 Annual Reports to the Congress of DOE, which project fuel declining 6.7%/year with electricity growing 2-3%/year. White area is use by existing buildings, which decline because of retrofit or replacement of old buildings; shaded area is use by new buildings, which need little fuel for heating, but use proportionally more electricity. For details see figure 13 in Rosenfeld-Hafemeister Commercial Building chapter. XBL 807-1450

Low Renewable potential is mainly from wind in rural areas; the High(ly unlikely) Renewable line includes some photovoltaics cells on roofs. Daylighting of commercial buildings is included, but is not counted as "renewable." (We classified it as a savings resulting from better design and controls.) The Potential savings is 200 of the 400 standard 1000-MW power plants serving the sector and, the potential wind generation could conceivably replace 30 more. If we take the cost of a new 1000 MW plant to be $1.5-2B, then 200 avoided plants saves $300-400 B, which roughly covers the capital necessary for our entire Least-Cost Scenario, even the non-electric investments that end up saving 5 quads/year of fuel.

These investments will be discussed below, but it may be appropriate to summarize them here. We conclude that we should invest about $2000 in each existing and new dwelling unit (100 million units by 2000), for a total of $200 B in residences. We should also invest about $2/ft.sq. of existing and new commercial space (50 billion ft.sq. by 2000) or $100 billion more. Finally, we would invest about $1250/home in more efficient appliances (furnaces, heat pumps, air conditioners, heat exchangers, water heaters, refrigerators, freezers, low-flow shower heads, etc.). The appliance investment of $125 billion is surprisingly large. The total investment is $425 billion, and it will save, in 2000 AD, about 16 quads. The average cost of conserving these 16 annual quads would be about $10/barrel of oil equivalent.

"Advancing the Market"

Of this 16 quads of annual potential savings by 2000, probably about half will inevitably be captured by action of the marketplace as energy prices rise. However, government and utilities can speed the process by sponsoring applied research, education, training of house- doctors and retrofit contractors, monitoring and evaluation of retrofit and new buildings, energy labels for appliances, homes, and commercial space. More controversial are tax credits for conservation, and performance standards for appliances and buildings. I am against most tax credits, but an argument for tax credits and standards is that they help correct a 10-to-1 imbalance in federal subsidies; annually new supply receives about $50 B, efficiency investments receive only about $1 B, but the gasoline tax ($6 B) favors conservation.[3]

o Comparison with Western Europe and Japan

This buildings summary has described a potential drop to half the energy use typically projected today. Roughly the same factor of one half applies to all sectors of the whole SERI Study, which gives a potential U.S. use dropping to 60-65 in 1983 annual quads by 2000, versus 74 today, and 100 projected by DOE for 2000.

It is of interest, then, to compare our potentials with what is already going on in Western Europe and Japan, where oil has been imported for a much longer time than in the U.S. and consequently has been more expensive and used more carefully.

Figure 4 allows us to compare the U.S. and Canada with these other countries. it is a scatter plot of energy use (per capita) versus income (per capita). Each country is a snake, with its tail at 1973 and its head at 1983. We can draw three inferences:

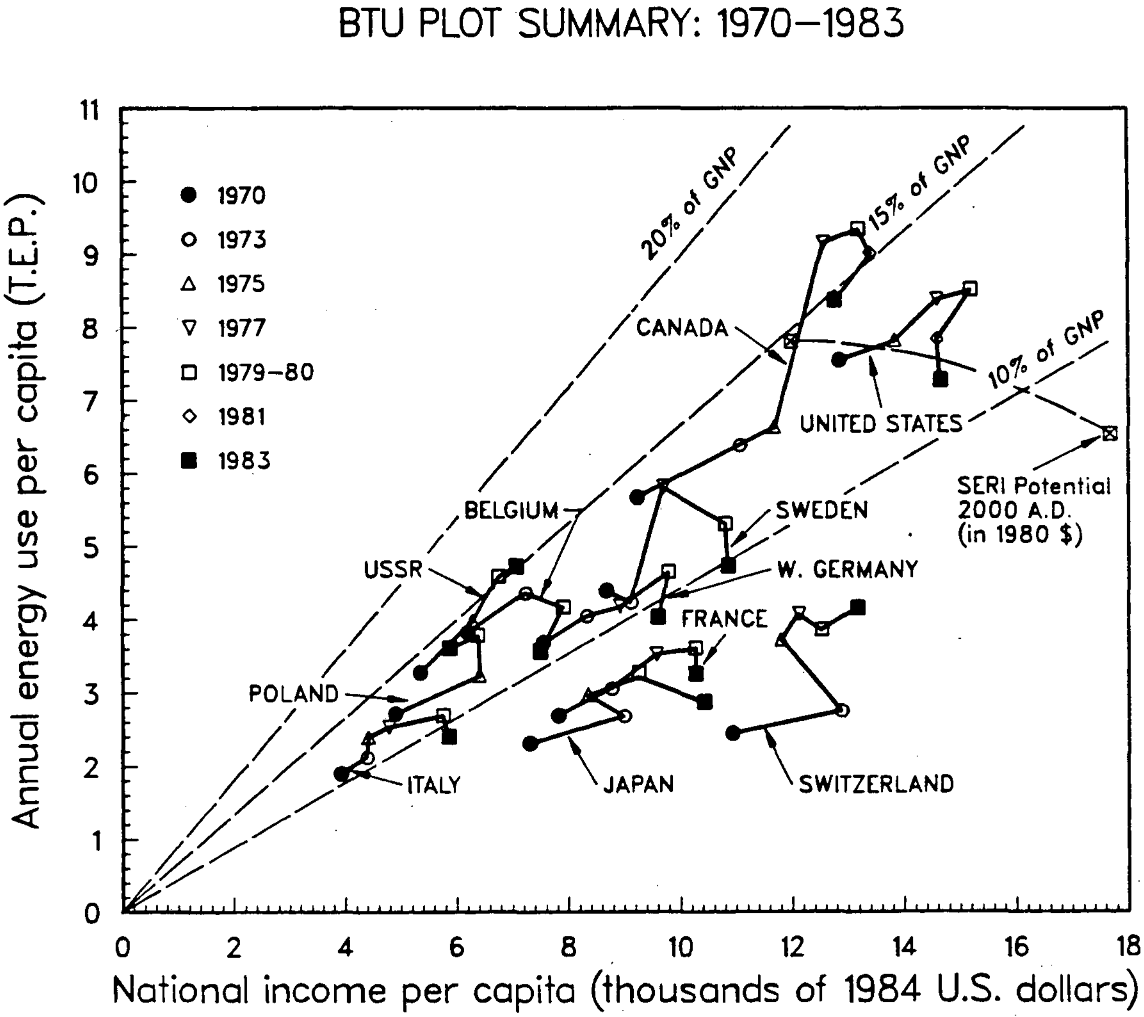

Fig. 4. Resource Energy Use vs. GDP (both per capita) For 11 Industrial Countries. Each country is a sequence of 7 or fewer points joined by straight lines. The conversion from local GDP to dollars depends only on the 1984 exchange rate; earlier points are plotted using individual national deflators. The energy data comes from the OECD/IEA volume "Energy Balances". In the case of income data, there are two different series (before and after 1980), so we scaled the incomes to match at 1980. We convert electricity to resource (primary) energy using the national heat rate (e.g., U.S. efficiency = 35%), except Japan, which uses a nominal efficiency of 35.1%, and 3 "hydro" countries, which use an OECD average efficiency of 37%. For the lines labeled 10%, 15%, and 20% of GNP, we use an average 1984 price of resource energy of $5.66/MBtu or about $226 per TEP. Conversion: 1 TEP (Tonne equivalent of petroleum) = 40 MBtu. Source for price: DOE/EIA 0376 (1983).

1. For the same income/capita, the rest of the industrial world has for a long time used only about half as much energy per capita as used by Canada, the U.S., and the USSR.

2. As energy prices rise and as more efficient cars, buildings, and industrial processes appear, the energy use per dollar of Gross Domestic Product (GNP corrected for exports and imports) is falling for all the countries plotted except the USSR, Poland, and Switzerland. The drop since 1980 is particularly steep. The buildings sector follows a similar trend; see Section III.

B. Supply Curves of, and the Cost of, Conserved Energy

This section follows closely Chapter 2 of our recent book[4].

o Defining Conservation

Consumers want the the services that energy provides, not energy itself. Furnaces burn gas to provide heat, air conditioners use electricity to cool and dry the air, and motors use electricity to provide mechanical drive. The amount of energy used for a particular service depends on the efficiency of the service mechanisms and the level of service demanded. One approach to energy conservation is to accept lower levels of service (turning down the thermostat, for example). Our approach, however, favors simple, economic measures that improve efficiency and save large amounts of energy without changing the service.

Trade-offs between energy efficiency and capital costs are common. *Figure 5* summarizes the progress in energy conservation for refrigerators. The California standard has progressively been improved from 1900 kWh/year in 1977, to 1500 kWh/year in 1979, to 1000 kWh/year in 1987, and to 700 kWh/year in 1993. The

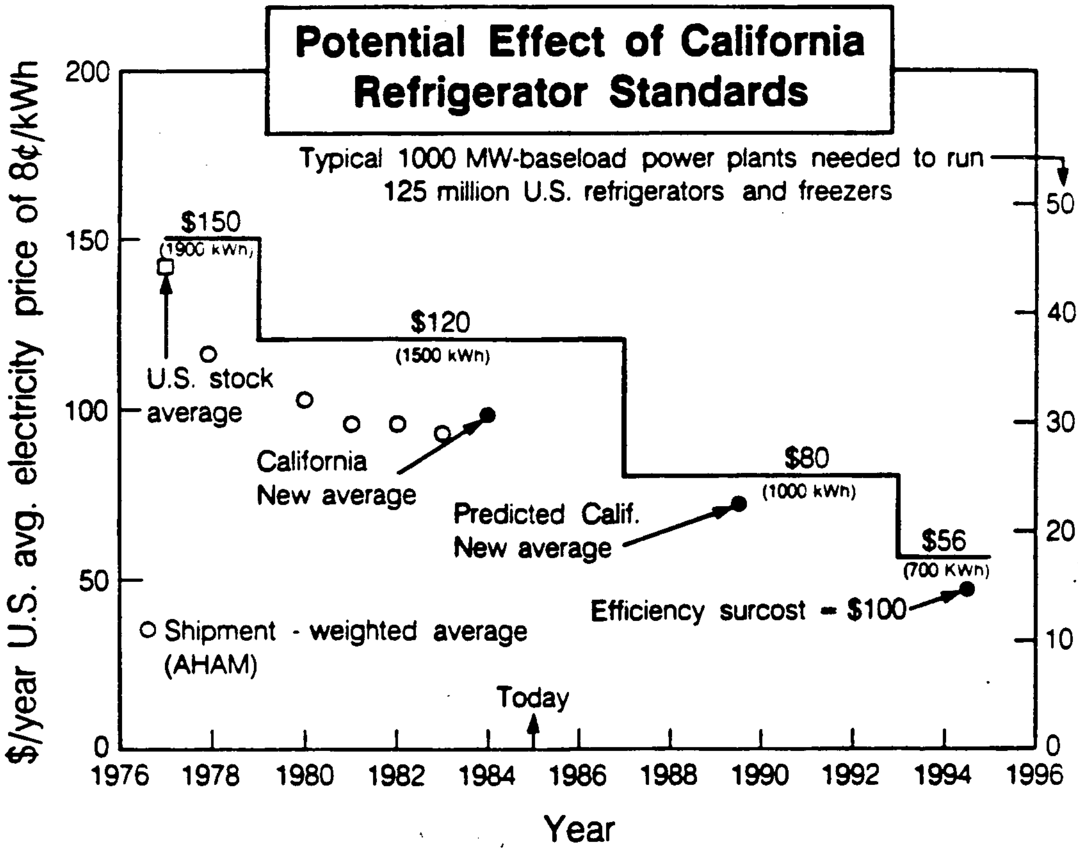

Fig. 5. California Mandatory Refrigerator Standards.
The standards reduce the average energy intensity from 1900 kWh/year in 1977 to 700 kWh/year by 1993. The additional cost of $100 retail for the 1993 standard will be paid back in one year (left-hand scale). The number of 1000-MW base-loaded power plants needed to run the nation's refrigerators and freezers is displayed on the right-hand scale. XCG 858-9882

additional cost to comply with the 1993 standard will have a payback period of one year since there will be a one- time cost of $100 to save $100/year for each of the remaining 19 years of the life of the refrigerator. Figure 5 also indicates the U.S. stock averages and the yearly production averages. the right-hand margin lists the number of 1000 MW-baseload power plants required to operate the 125 million U.S. refrigerators and freezers; the improved refrigerators will save the need to operate about 30 power plants when compared with the 1977 U.S. stock average.

o A Supply Curve of Conserved Energy

A supply curve for any energy source ranks the various reserves of that energy in order of increasing cost and shows how large each reserve is. *Figure 6* depicts supply curves for two grades of coal. A supply curve of conserved energy is the analog of a supply curve for reserves of gas, coal, or other tangible energy resources--the curve slopes upward since more conserved energy becomes available only at increasing costs. The reserves of conserved energy can be tapped by a sequence of conservation measures, each having its own size and cost.

To develop a supply curve of conserved energy, two values must be found for each measure. The vertical coordinate (y-value) of a conservation measure is the unit cost of the energy conserved by that measure; the horizontal coordinate (x-value) is the cumulative energy saved annually by that measure and all measures preceding it in the supply curve. *Figure 7* is an actual supply curve, Fig. 1.40 of the SERI Study[1]. Determining the y- value (unit cost) requires engineering and economic data; determining the x-value (savings) requires research into the characteristics of the energy-using stock. We discuss these two types of investigations in detail in the next two sections.

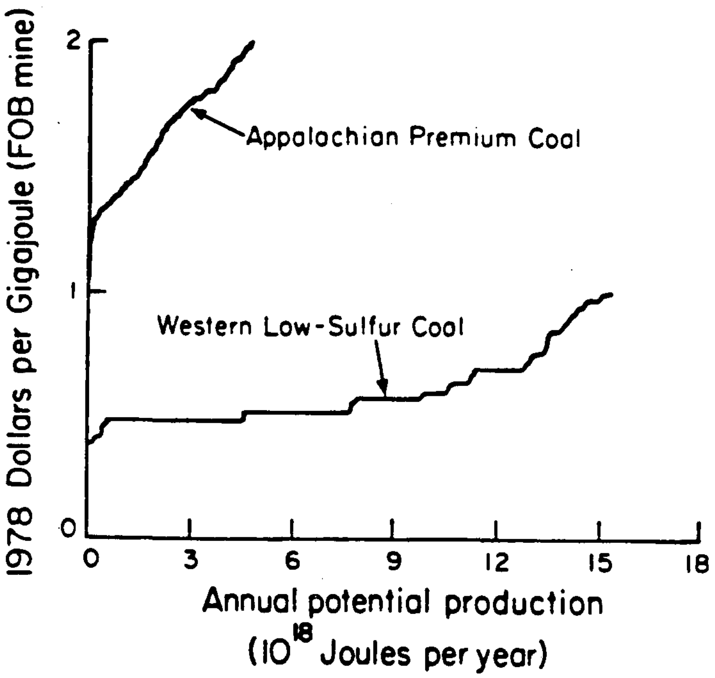

Fig. 6. Supply curves for two grades of coal. The reserves of Western coal are cheaper and three times as large as the reserves of the Appalachian coal. Source: EIA 1978.

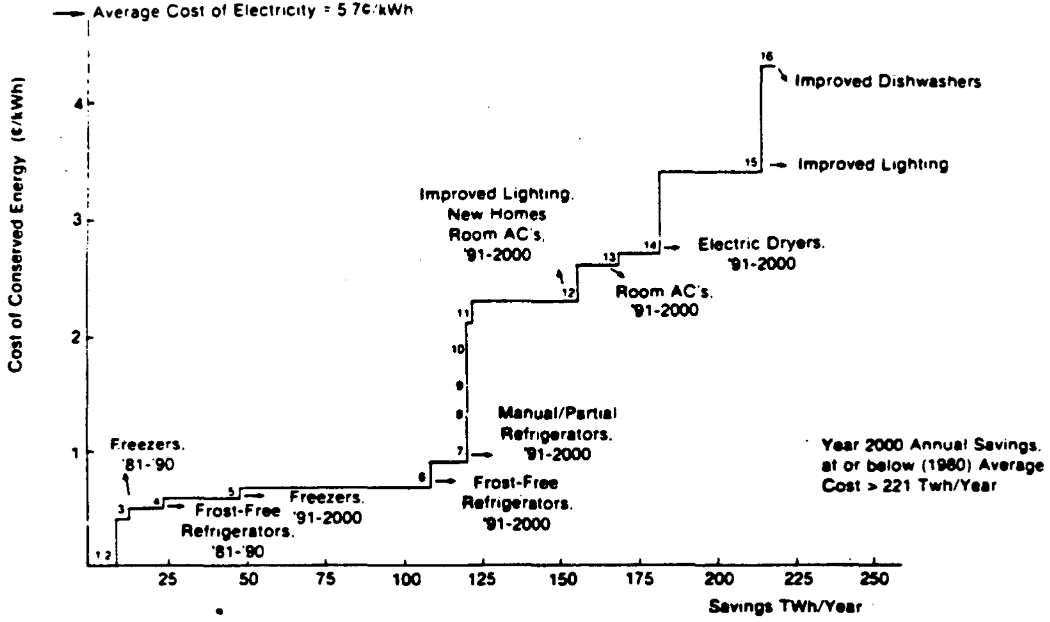

Fig. 7. Year 2000 Supply Curve of Conserved Energy (in Twh/year) for Electric Appliances. Year 2000 baseline annual use for this sector is 581 Twh, where "baseline" assumes continuation of 1980 average unit energy consumption for existing stock or new additions in that year. Unit cost of conserved energy (in constant 1980 $) assumes that all increased costs are amortized over the useful life of the measure, using a 3% (real-dollar) interest rate. Potential savings in 2000, at or below 1980 average cost of $0.057/kWh is 221 Twh, or 38% of the year 2000 baseline. Source: SERI Solar/Conservation Study, Brick House Press, 1981.

° The Cost of Conserved Energy

To establish the unit cost of the conserved energy CCE, such as cents per kWh, the annualized investment I in conservation (for materials and labor) is divided by the annual energy savings E:

$$\text{CCE} = \frac{\text{Annualized Cost}}{\text{Annual Energy Savings}} . \qquad (1)$$

Since investment (I) actually occurs just once, it must be annualized by multiplying it by the "capital recovery rate," CRR,

$$\text{CRR} = \frac{d}{1 - (1+d)^{-n}} , \qquad (2)$$

where "n" is the number of years over which the investment is written off, or amortized, and "d" is the discount rate. The unit cost is thus determined by the formula:

$$CCE = \frac{I \cdot CRR}{E} = \frac{I \cdot d}{E\,[1 - (1+d)^{-n}]} \quad . \qquad (3)$$

Let us take an example. A consumer wishes to buy a new refrigerator. We compare the 1977 model with the 1993 model of Fig. 5. The high-efficiency model (offering services identical to the standard model) costs $100 more but uses 1200 kWh per year less electricity. The consumer wants to recover his investment in 20 years (the useful life of a refrigerator). The consumer has a "real" (after inflation) discount rate of 5% (at an inflation rate of 5%, this would be equivalent to borrowing at 10%). The cost of conserved energy in this case is:

$$CCE = \frac{\$100}{1200\ \text{kWh/yr}} \times \frac{0.05}{1 - (1.05)^{-20}}$$

$$= \frac{\$100 \times 0.08}{1200\ \text{kWh}} = 0.7¢/\text{kWh}$$

For the case of a shorter-lived appliance (10 years), the CRR rises from .08 to .13, giving CCE = 1.1¢/kWh.

Compared with paying the utility 7.5¢/kWh (1984 U.S. residential average), it is very profitable to pay only 1¢/kWh saved by purchasing an efficient refrigerator where one's old one needs replacing.

Furthermore, the cost of the <u>conserved</u> electricity will stay the same for the 20-year life of the refrigerator. In contrast, the <u>real</u> price of electricity will most likely "escalate," that is, exceed general inflation. Note that the <u>cost</u> of the conserved electricity is independent of the <u>price</u> of electricity. The payback period in avoiding the 7¢/kWh electricity with the $100 investment is 1.1 years.

Calculating the cost of energy "supplied" by a conservation measure thus involves four variables:

1. Investment (initial) of the conservation measure.
2. Annual energy savings expected from the measure.
3. Amortization period of the investment.
4. Discount rate of the investor.

These variables are analogous to the criteria for investment in the supply sector:

1. Cost of extraction facility.
2. Rate of extraction.
3. Depreciation of facility (and possible depletion of the reserve).
4. Discount rate of the firm.

In the rest of Chapter 2 of Meier et al.[4], we discuss each of these four variables in detail, but our procedures are summarized on page 14 of the SERI Study.

1. For investment cost, we took contractor costs or retail prices of appliances.

2. For annual savings, we took empirical data where available; if we had to use calculations, we scaled them to agree with measured results.

3. For amortization, we took the shorter of the physical life of a measure, or 20 years.

4. For real discount, rate we distinguished between:

   a) 3% real for residential investment, corresponding to the historic real interest rate on mortgages.
   b) 10% real for commercial buildings, where energy investments have to compete with investments for more production and profit.

o "Conservation" or "Least Cost" Potential

We define the potential from the consumer's point of view, i.e., where the supply curve crosses the consumers price for fuel or electricity.

Please note that although we define the residential (commercial) potential corresponding to a 3% (10%) real discount rate, the reader can easily select any rate he chooses. Thus, after we calculate our "grand supply curves" (Fig. 16 below), we recalculate them for 3%, 10%, 30%, and 40%. We see that an increase in the perceived consumer discount rate from 3% to 30% loses roughly half the potential savings. We look on this not only as a sensitivity analysis, but a nice way to estimate the potential savings attributable to information programs and labels, which effectively remove uncertainty and risk, and lower the consumer's discount rate towards the 3% and 10% values available for home mortgages or commercial borrowing.

o Time Perspective for a Conservation Potential

A potential energy savings is, of course, a function of one's time horizon. Since we are interested in changes in efficiency, not behavioral changes, nothing can be done overnight. For the SERI Study, we chose a 20-year perspective. In 20 years most appliances will have worn out at least once and been replaced with more efficient models. By 2000, 20 million of the 1980 count of 80 million dwelling units will have vanished, the remaining 60 million will have been retrofit, and 40 million new ones will be built. Unlike homes, which have a mean life of about 100 years, commercial buildings last only 40 years. So, by 2000, 20 B ft^2 of our current 50 B ft^2 of commercial floor space will have vanished, but the total will have risen to 62 B ft^2, i.e., 32 B new ft^2 will have been added.

o Why Use "Resource" Energy Instead of "Site" Energy?
i.e., What is the energy value of 1 kWh of electricity?

In many of our figures, electricity and fuel both enter--and we want to express them to be of comparable dollar value. Restated: we are not interested in conserving energy per se, only in reducing the cost of the services that it supplies. But fuel and electric prices are unstable, so people like to work in units of energy. If we convert to Btu 1.0 kWh of electricity as if it were electric resistance heat (1 kWh liberates 3415 Btu of heat within the building), we find that it costs about $20/MBtu, while gas and oil cost only about $7/MBtu. But if we convert electricity according to the heat used back at the power plant to generate 1 kWh (11,600 Btu burned per kWh generated, transmitted, distributed, and sold), then electricity costs $7/Btu of "resource" or "primary" energy (the same as the price of oil). Hence, from our point of view, it makes sense to use resource energy when comparing electricity and fuel.

o More Examples of Supply Curves and the Cost of Conserved Energy

To give some physical examples, we introduce another pair of figures. *Figure 8* is an energy-cost curve for retrofitting an existing home, and *Fig. 9* is the same set of calculations replotted and reordered as a supply curve of conserved resource energy.

TABLE II. COST OF CONSERVED GASOLINE, assuming a car is driven 10,000 miles/year and lasts 10 years.

			ANNUAL			
YEAR	MILES PER GAL	EXTRA FIRST COST Δ$	GAL USED	GAL SAVED	LOAN PAYMENT ($)*	COST OF CONSERVED GASOLINE (¢/GAL)
1975 Fleet	14	0	700	0	0	--
1985 Standard	27.5	1000	350	350	160	45¢
1995 Proposed	40	1500	250	450	240	53¢
1995 Import (VW RV 2000)	65	2000	150	550	320	58¢

I. CRUDEST ARGUMENT:

$$\frac{\text{INCREASE FIRST COST}}{\text{TEN YEAR GAS SAVED}} = \frac{\$1000}{350\ \text{GAL}} = \frac{28¢}{\text{GAL}}$$

*II. USING 10% "REAL" INTEREST RATE, (ie., in constant $):

A 10% bank loan, repaid in 10 constant annual payments, costs $160/y

$$\frac{\text{ANNUAL COST}}{\text{ANNUAL SAVINGS}} = \frac{\$160}{350\ \text{GALLONS}} = \frac{45¢}{\text{GAL}}$$

- This calculation has nothing to do with the price of gasoline, i.e.

Current Price of Gasoline	-	$1.30/GAL
Price of Synfuels	-	$2-3/GAL

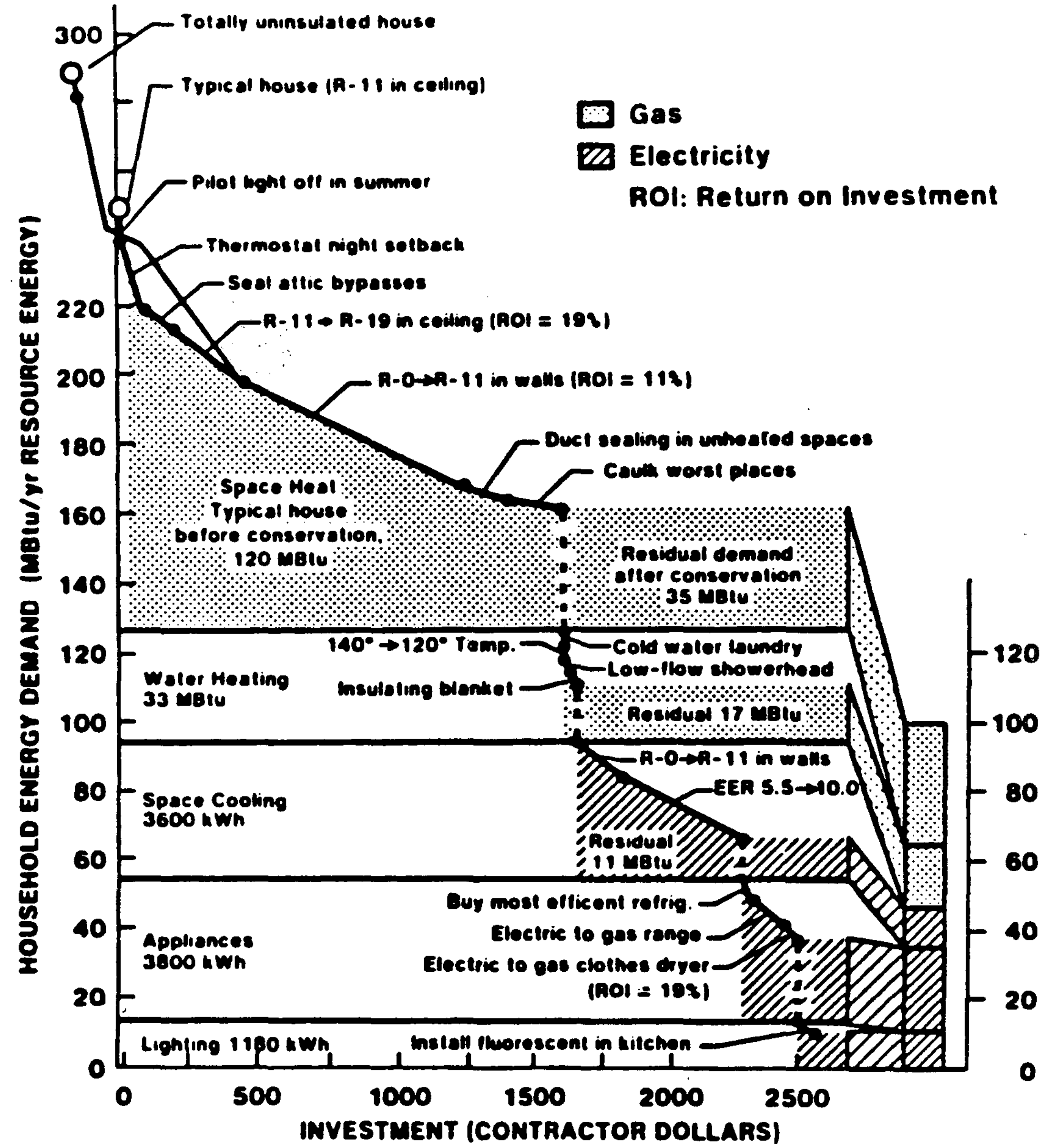

Fig. 8. Retrofit Conservation Potential in a Northern California Single Family Home, Gas Heat. (1200 sq.ft., 3000 Heating Degree-Days) XBL 812-7946 (See figure 9).

Table II switches temporarily from buildings to cars. It compares the 1975 "gas-guzzler" with the 1985 "social drinker." It shows that even if we include the cost of the catalytic converter (which is added to abate pollution, not to save energy), the cost of conserving a gallon is still 45¢, much cheaper than buying a gallon for $1.30. Again this illustrates the nice feature of using the cost of conserved energy--it makes it trivial to tell whether to invest in efficiency or in new supply.

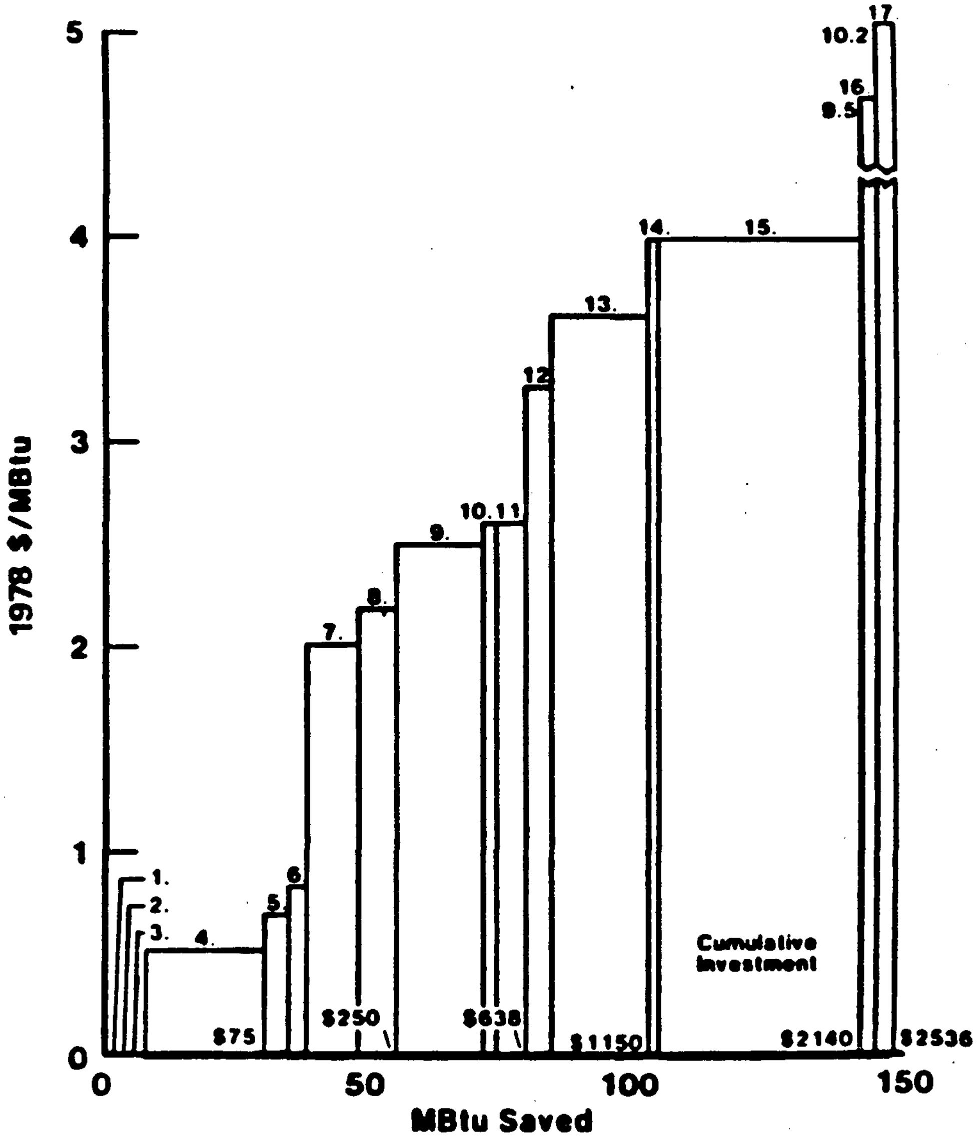

Fig. 9. Retrofit Conservation Potential in the Northern California Single Family Home, replotted as a conservation supply curve. Cost of conserved energy in $/MBtu of resource energy, calculated using 10% cost of money, plus depreciation, with all installation done by a contractor. Total annual energy consumption of the house before retrofit was 250 MBtu/year.

1. Turn furn. pilot off in summer.
2. Reduce hot water temperature, 140 to 120 degree-F.
3. Cold laundry rinse.
4. Thermostat night setback to 60 degree-F.
5. Buy most efficient refrig.
6. Install low-flow shower head.
7. Furnace tune-up (biennial).
8. Change from electric to gas range.
9. Increase ceiling insulation, from R-11 to R-19.
10. Install fluorescent lighting in kitchen.
11. Change from electric to gas clothes dryer.
12. Seal attic bypasses.
13. Change to high-efficiency air conditioner, EER 5.5 to 10.0.
14. Install water heater insulating blanket.
15. Insulate walls, R-0 to R-11.
16. Seal and insulate ducts in unheated spaces.
17. Caulk building shell (in worst places).

XBL 812-7947

At LBL (Lawrence Berkeley Laboratory), we have for many years been pursuing the concepts of Cost of Conserved Energy, and Conservation Supply Curves, with considerable success. The California Energy Commission and the Northwest Power Planning Council have adopted them, but unfortunately most energy planners still do not treat efficiency and supply investments symmetrically; thus our tax credits and deductions, and other subsidies, contribute annually about \$50 B to investments in <u>supply</u> and less than \$1 B to investments in <u>efficiency</u>[3] .

o Simple Payback Period

The concept of cost of conserved energy CCE is useful to policymakers for two reasons: (1) Conservation and production can be discussed together on the same footing since the costs of supply and demand are in the same units such as ¢/kWh or \$/barrel. (2) Since CCE is calculated without reference to the utility price P, or guesses as to the future price of energy, one can calculate CCE once and for all and not have to repeat it for every utility and cost scenario.

On the other hand, the consumer usually is concerned with the return on his investment which can be expressed in terms of the simple payback period, the time to recover his investment in the conservation technology, or

$$SPT = I/P\,e. \qquad (4)$$

By dividing Eq. 4 by CCE (Eq. 3), we obtain

$$SPT = (1/CRR)\,(CCE/P). \qquad (5)$$

For the first example of the refrigerator, SPT = (1/0.08) (0.7/7.5) = 1.1 years.

III. RESULTS FOR THE RESIDENTIAL SECTOR

In the SERI report[1] you will find eight residential supply curves; "eight" because there are two types of energy (fuel and electricity), times four subsectors (homes new and existing, hot water, and appliances). We used computer simulation as little as possible and always normalized their results to empirical data. In this section I want to discuss some of the data, because they add reality and contribute confidence to the results. Although the discussion refers to the 1980 SERI study, all the data below are more modern.

At LBL, our Buildings Energy Data Group publishes a series of review articles called BECA (Buildings Energy Use Data and Critical Analysis), and most of the following figures are from BECA.

o Retrofit of Existing Homes

Figure 10 is a scatter plot of 47 different retrofit projects or experiments, each experimental point involving typically 10-20 homes. To be cost effective, each point must fall above the sloping lines representing the current prices of electricity, gas, and oil. Restated in terms of our "cost of conserved energy"--a point <u>on</u> the line will have a <u>cost</u> of energy just equal to the <u>price</u> of energy. You can see that overwhelmingly the retrofits are cost effective and lead to a 35-40% savings for an average cost of \$1370. Note also the CSA/NBS open circles

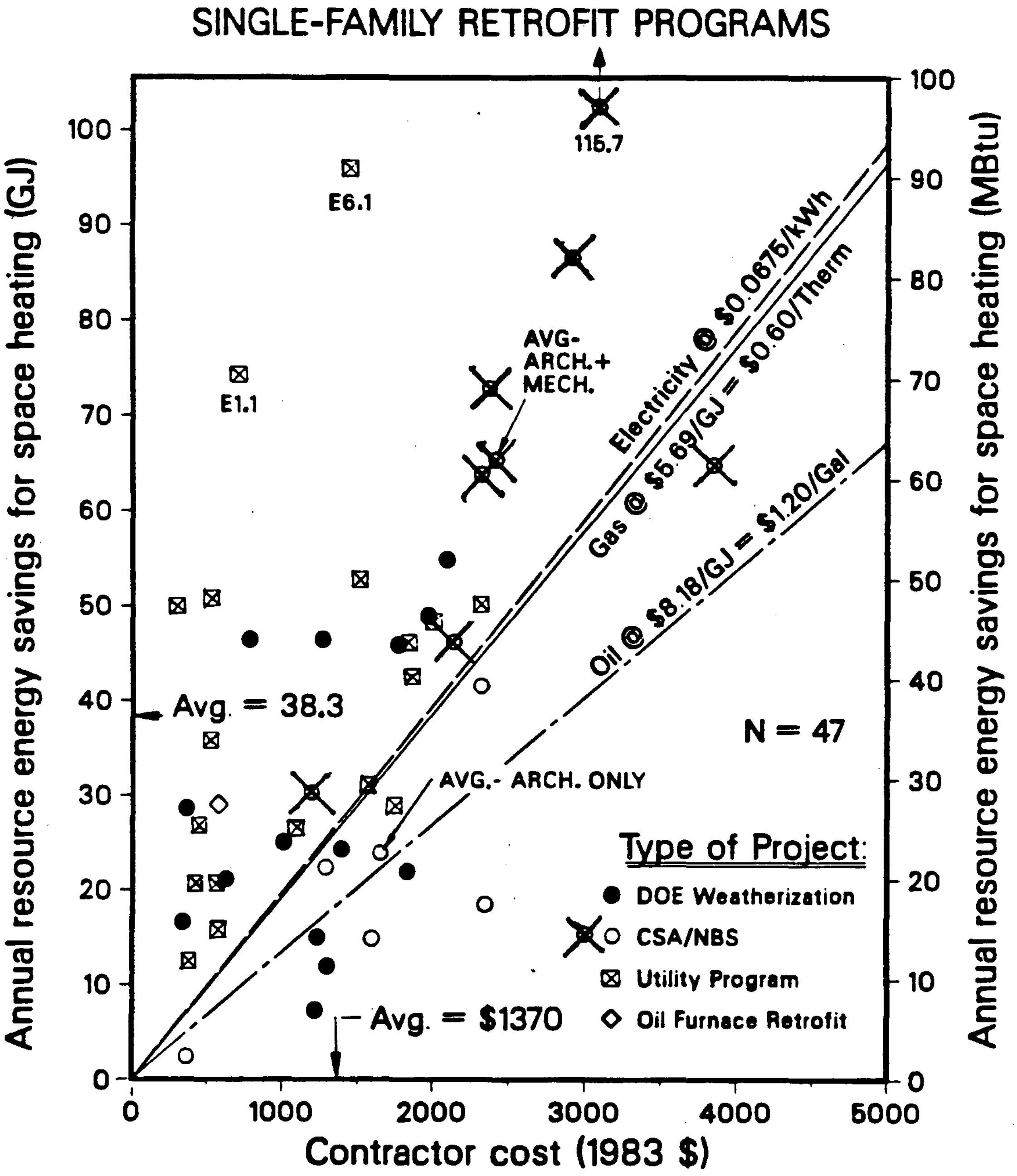

Fig. 10. Annual space heat energy savings are plotted against the first-cost of the retrofit investment for utility-sponsored or low-income weatherization programs. Average space heat savings are 36.3 million Btu (MBtu). The 47 data points represent results from over 50,000 homes. The sloping reference lines show the minimum energy savings that must be achieved, for each level of investment, if the retrofit is to be cost-effective compared to national average residential prices for fuel and electricity. The future stream of energy purchases for 15 years, assuming constant energy prices (in 1983 $), is converted to a single present-value, using a 7% real discount rate, in order to compare it with the "one-time" conservation investment. Roughly 75% of the data points lie above their respective reference line. Electricity is measured in resource units of 11,500 Btu per kWh. Source: BECA-B (Oct. 1983). XCG 839-7233

showing that "architectural" measures (insulation and other repairs to the shell of the home) are less effective alone than the big X's which are CSA results when shell retrofits were combined with "mechanical" retrofits, i.e., repairs and tune-up of the heating system.

How well do measured saving agree with predictions made by home auditors? From project to project, there is great variation in the ratio of saved/predicted, but averaged over hundreds of homes, we find that 2/3-to-3/4 of the predicted savings are actually achieved[5]. This shortfall (and the fluctuations) can be explained by many factors: poor auditing, inadequate quality control, and finally "respending" (i.e., the occupant plugs leaks and then decides he can now afford to

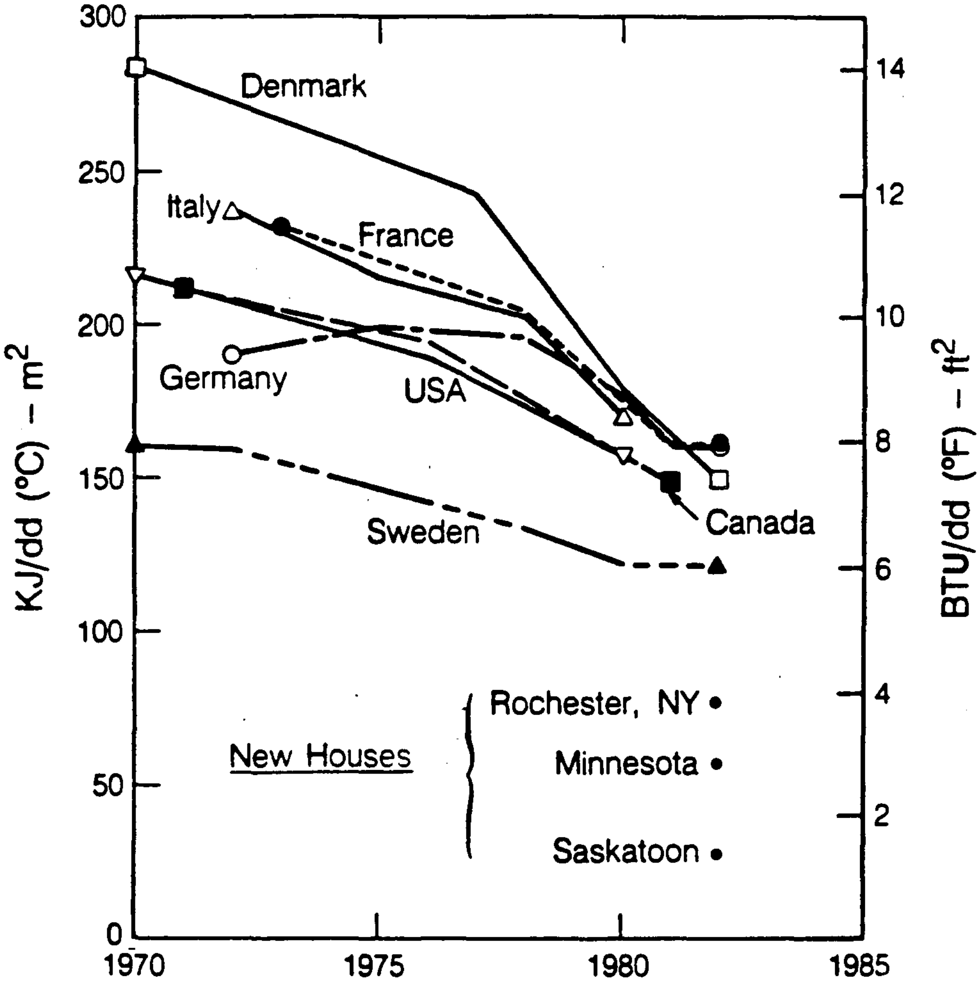

Fig. 11. Residential space heating *load* (useful furnace output) per degree-day for existing homes. To convert to English units use 1 kJ/m^2-dd(°C) = 0.049 Btu/ft^2-dd(°F). The new houses data are from a BECA survey of 175 new homes by J. Busch, A. Meier, T. Nagpal, American Council Energy Efficient Economy, 1984 and LBL-17883. Source: L. Schipper, A. Ketoff, A. Kahane, Annual Review Energy 10 (1985). LBL-19448.

heat additional rooms). Unfortunately, there has been very little monitoring before-and-after retrofit and little post-retrofit inspection, so it is difficult to sort out these factors and "tune up" the audit/retrofit industry.

The trends in international residential space heating, tracked by Schipper, Ketoff, and Kahane[6], are plotted in *Fig. 11.* United States space heat per m^2 has dropped 25% in 5 years, but sadly most of the conservation has come from lifestyle changes and not from retrofitting. For commercial buildings as a whole, fuel use/ft^2 has dropped 4%/y and electrical use has grown 0.7%/y.

o New Homes

Figure 12 compares the heat needs of various U.S. homes. It presents the same data as already plotted as a time-series in the right-hand part of Fig. 2, but this time the x-axis is the climate, measured in "heating degree days," and the units are heat (i.e., furnace output, not fuel as in Fig. 2). The higher dashed line represents the "Stock" of Fig. 2; the lower dashed line is the improved 1979 home-building practice; the solid BEPG lines are computer-optimized homes; both have 0.7 air changes per hour, but the lower line assumes heat recuperation from the exhaust air with an "effectiveness" of 2/3.

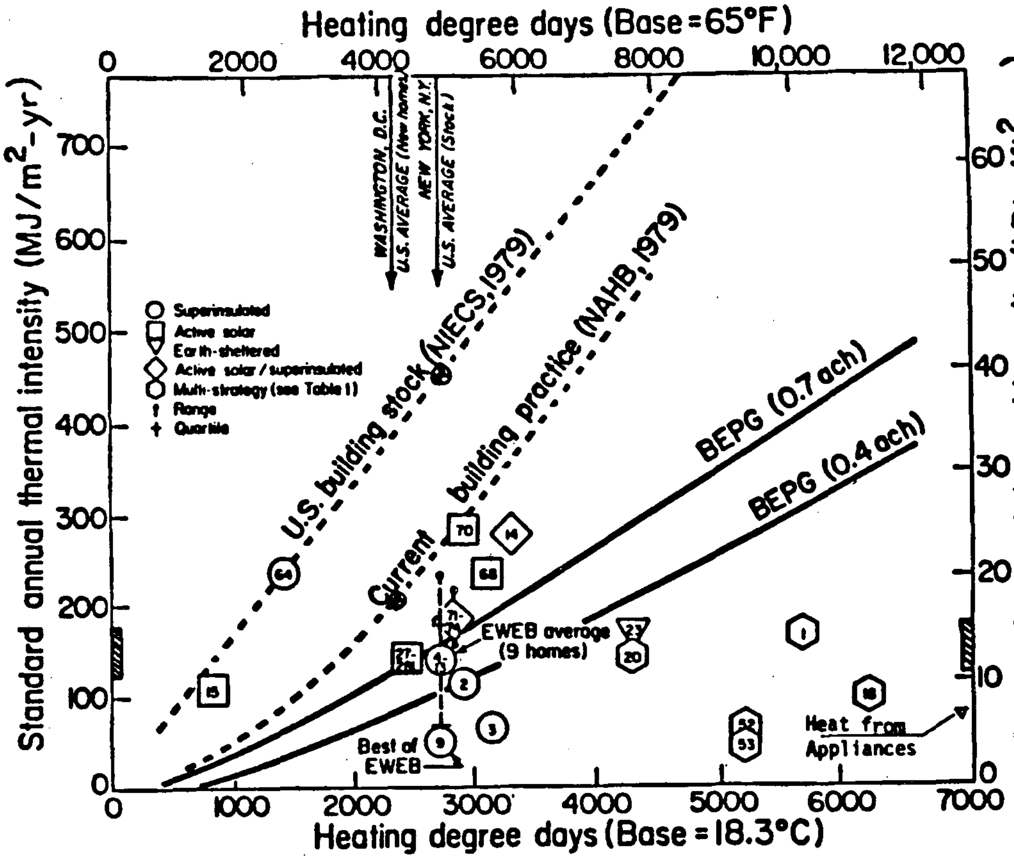

Fig. 12. Thirty-seven home scatter plot of "standardized" thermal intensity vs. climate. The various comparison curves are defined in the text. The average thermal intensity per degree-day for our 37 homes is 50 kJ/(m^2-°C-day), or half of the current building practice. Shaded bars represent typical annual water heating use - comparable to space heating in the low-energy homes shown. 5 months of winter heat from appliances is approx. 6.5 kBtu/sq.ft. Source: BECA-A (1983).

On Fig. 12, note the many superinsulated and passive solar homes with thermal intensities of 10-20 kBtu/ft^2 , which is even below the theoretical BEPG (Building Energy Performance Guidelines), for reasons already discussed in Section I. Figure 12 displays only those points in the BECA-A collection where there were enough measurements to correct each house to standard occupancy conditions; but *Fig. 13* displays many more points where internal temperatures and/or appliance usage were not measured--but where it is still clear that 20 kBtu/ft^2 is adequate even in Saskatchewan. For a 1500 ft^2 home, this translates to 30 MBtu/winter; for a modern gas furnace with an efficiency of 90%, the annual heating bill is then down to $200.

Figure 14 shows that most of these low-energy homes are <u>cost effective</u>. As in Fig. 10, a point on one of the sloping lines (i.e., gas at $5.60/MBtu and a 3% real interest rate) has a cost of conserved energy just equal to the price of the gas. We see that many points lie above these "indifference lines." The key (circles for superinsulation, triangles for passive solar,...) shows the strategy used. It has been very hard to find good data for active solar homes. We started with many leads, but had to throw out most of them for one of three reasons:

1. Poor thermal data,
2. Poor cost data,
3. Not measuring the "auxiliary" thermal output of a wood stove.

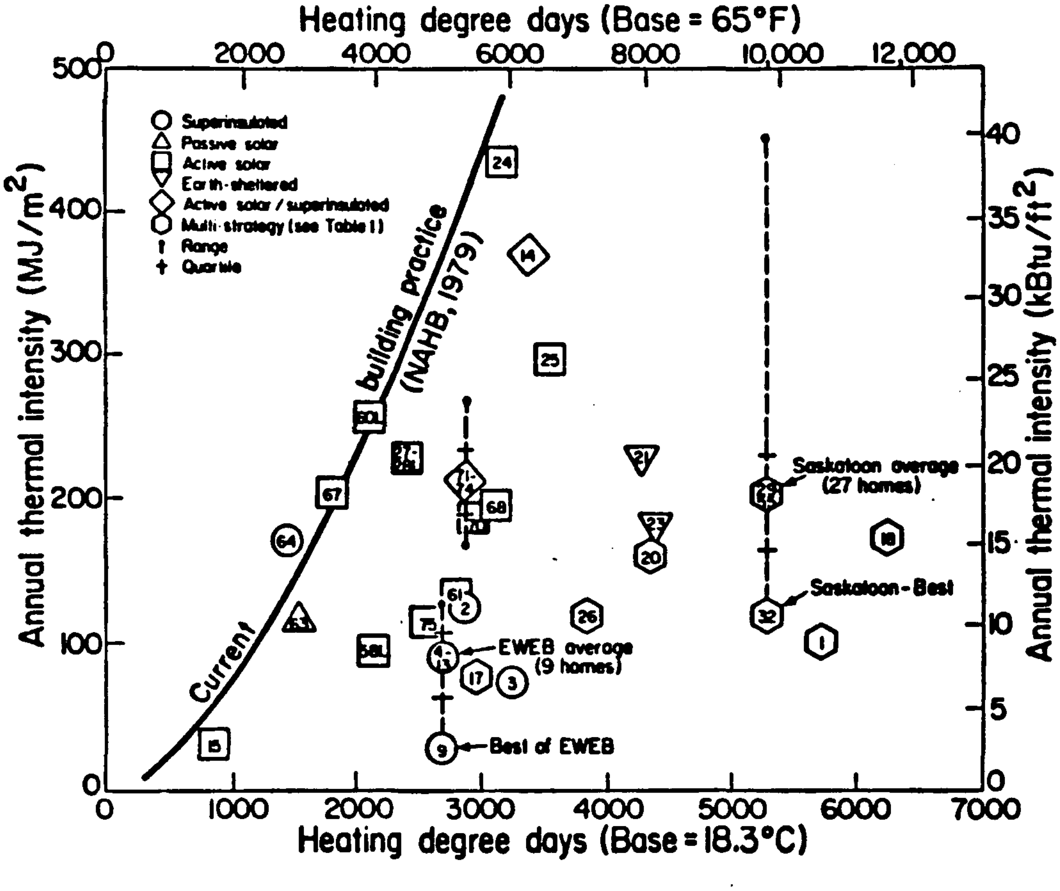

Fig. 13. Scatter plot of annual heating load/m^2 vs. climate for 28 points representing 128 sub-metered energy-efficient new homes. The solid curve is NAHB's 1979 survey of U.S. building practice, taken from Fig. 12. Source: BECA-A (1983).

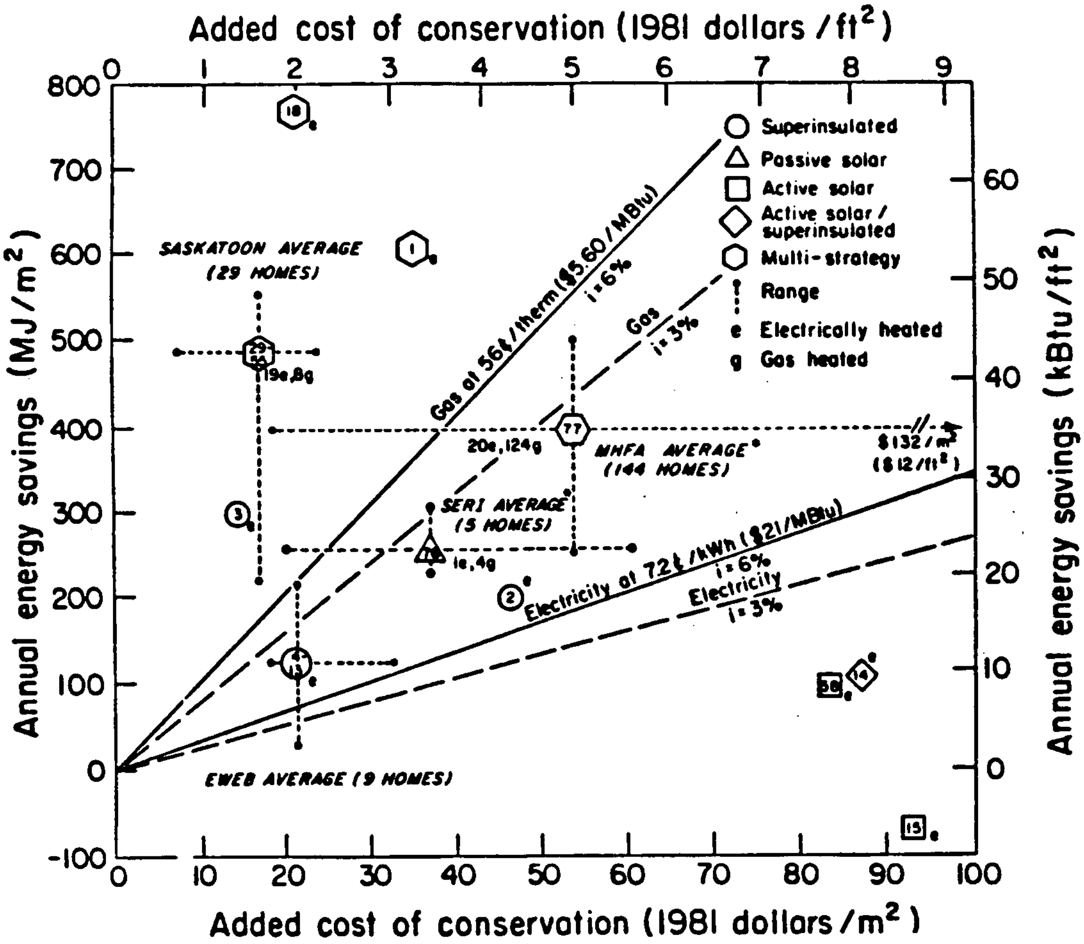

Fig. 14. Annual energy savings vs. added cost of conservation. Both savings and added cost are relative to 1979 current building practice curve labeled NAHB, 1979; thus a point at 0,0 would be a typical 1979 home. Source: BECA-A.

Several active solar houses did pass our criteria, but they are all economic failures. We are still eagerly looking for successes, but the basic economic problem is that superinsulated and passive homes need only $200 of fuel for the winter, all of it during a few cold months when the days are short and the sun is low. This makes it almost impossible to justify investing many thousand dollars in solar collectors. Note that this is not an argument against active solar domestic hot water systems which collect heat all year round.

I hope by now to have convinced you that we have enough empirical data to calibrate our supply curves for new homes. The actual curves can be found in the SERI Study[1] .

- Appliances (Refrigerators)

I'll try to give you a feeling for the potential for increasing the efficiency of appliances by discussing a single figure, 15, on refrigerators [Rosenfeld and Goldstein, 1978].

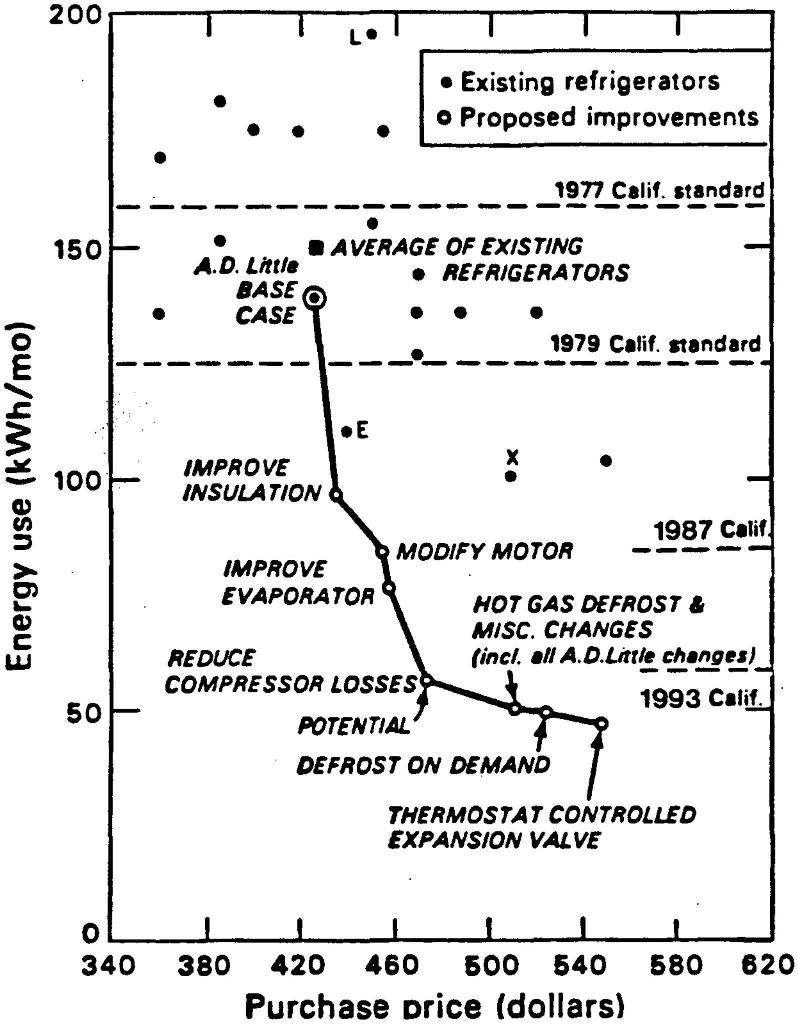

Fig. 15. Electricity use vs. purchase price for existing and proposed refrigerators. The closed circles in the upper half of the figure represent 16-17.5 cu. ft. top-freezer, automatic defrost models sold in California in 1976. The open circles joined by a heavy line are improved design steps proposed by A.D. Little (May 1977). All U.S. refrigerators plus freezers in 1980 used about 140 BkWh, so the vertical scale can also be read in BkWh, for the U.S. The potential savings of 85 BkWh is the output of 17 1000-MW baseload power plants. See figure 5 for the evolution of California refrigerator standards. XBL 7712-11464, from LBL 6865 (CA Policy Seminar)

Figure 15 dates back to 1976, before there were any appliance efficiency labels. The solid dots in the upper half of the figure represents 16-to-17.5 ft^3 automatic defrost top-freezer models for sale in California in '76. The first thing to point out is that there was almost no correlation between efficiency and price. By buying model E (for Economical) instead of model L (for Lemon), a homeowner could save 1000 kWh/year, worth (in 1976) $50/year, i.e., $1000 over the 20-year life of the refrigerator. It was data such as these that convinced the California Energy Commission that appliance standards would cost the consumer nothing and yet (for refrigerators and freezers alone) would save California 1-2.5 power plants over 20 years.

With the advent of appliance efficiency labels, there is now some mild correlation between efficiency and price, but the wise comparison shopper can still save hundreds of dollars of electric bills by investing an hour on the phone asking about prices and then calculating life-cycle costs. One further remark about appliance pricing: In Fig. 15, model X is the most efficient, but by no means the most economical. This trend persists today for most appliances and equipment. The new, efficient, highly- advertised model is almost never the most economical to buy.

So much for pricing questions--what improvements are practical? The open circles joined by a heavy line are improved design steps proposed in 1977 by A.D. Little. We should point out that several manufacturers have since produced models corresponding to the "Potential" point and are selling them for about the price indicated on the figure [see chapters by Geller and Levine in this book].

Noted on Fig. 15 (which dates from 1977) are the subsequent California mandatory refrigerator standards. They show that as prices and energy awareness both rise, engineering calculations can indeed be realized in the market place, if helped by public policy. However the delay is about 20 years, plus an added 20 years for all the existing stock of refrigerators to wear out and be replaced.

The 1¢/kWh cost of conserved energy of these better refrigerators was calculated in Sect. II just below the equations for CCE.

For manufacturers it is easy to satisfy the California standards, so whenever California updates, the manufacturers have been following for the whole U.S. Hence, in Fig. 5 we added a right-hand scale of power plant savings for the entire U.S.--30 standard plants when the 1993 standards propagate into the stock.

It should be no surprise that refrigerator improvements are a significant contribution to conservation supply curves for appliances, such as Fig. 7.

o Grand Supply Curves for the Residential Sector

I have tried above to give you a physical understanding for the sorts of options that go into the eight supply curves for the residential sector. The individual supply curves are in A New Prosperity, and the grand ensemble is displayed in *Fig. 16*. Each curve is calculated four times, for four different discount rates, ranging from 3% real (the low interest that corresponds historically to a home mortgage, where there is good information, security for the bank, and minimal risk to the lender) to 30% real (more characteristic of the appliance market, with its poorer information and security).

If we had good information programs (labels, fact sheets, buying guides) and perhaps standards, we could use the supply curves corresponding to 3% or 10% discount rates, and read off a potential for saving 500 or 550 BkWh (the output of about 100 plants). As the "implicit discount rate" rises to 20% we see that about 40% of the potential savings are lost, but then a discount rate rise from 20% to 30% does not make a lot more difference. This family of curves is a good way to display both the physical and information potential of conservation.

The lower figure tells the same story for fuel. We see that for a 3% real discount rate and the December '80 price of fuel oil (which is about the December '83 price of natural gas), there is a potential savings of about 6 quads out of the 9 needed for the base case. If the implicit discount rate rises to 20%, again about 40% of the potential is lost.

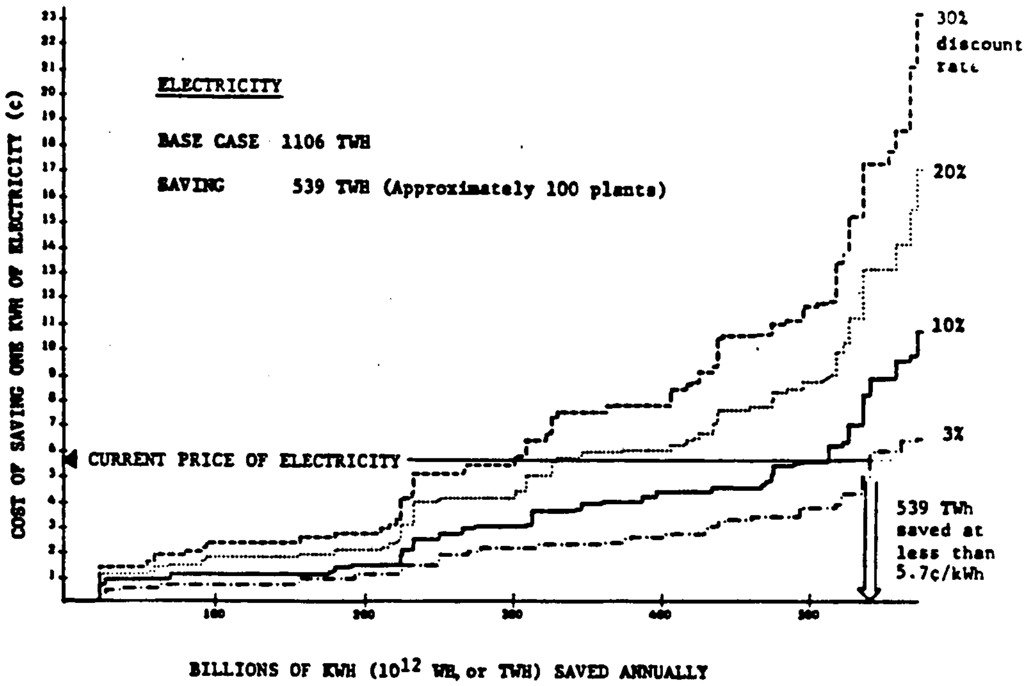

Fig. 16(a). Supply curves of conserved electricity for the U.S. residential sector (retrofit of stock, plus 20 years of construction) in the year 2000. Four curves are plotted, each corresponding to a different real discount rate. LBL-11300

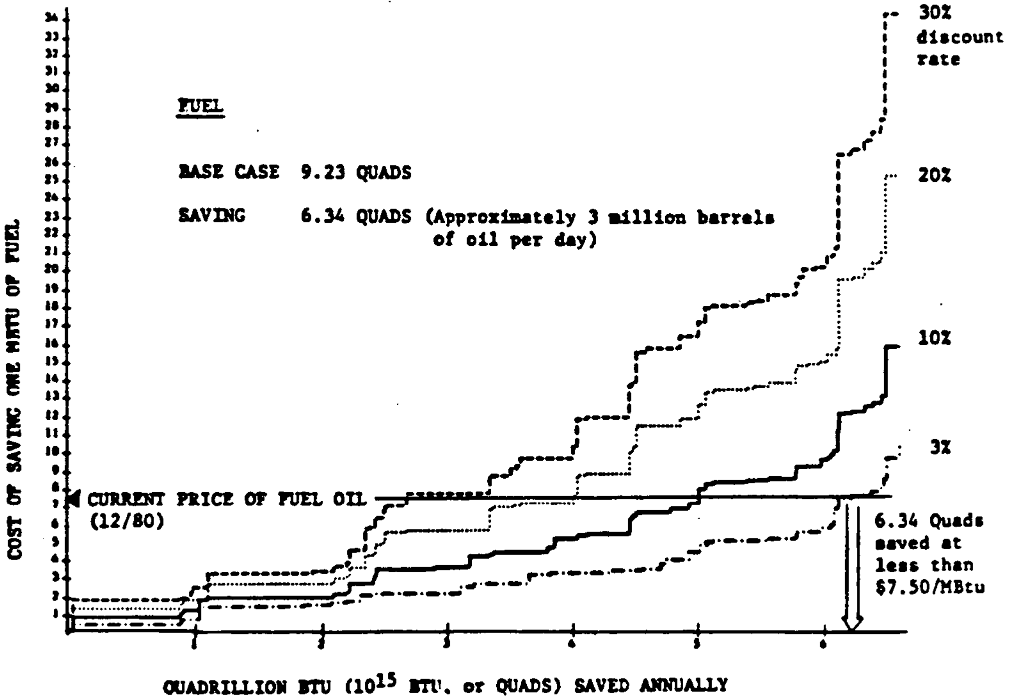

Fig. 16(b). Supply curves of conserved fuel for the U.S. residential sector (retrofit of stock plus 20 years of construction) in the year 2000. Four curves are plotted, each corresponding to a different real discount rate. Source: LBL/SERI Buildings Study. LBL-11300 (April 1981)

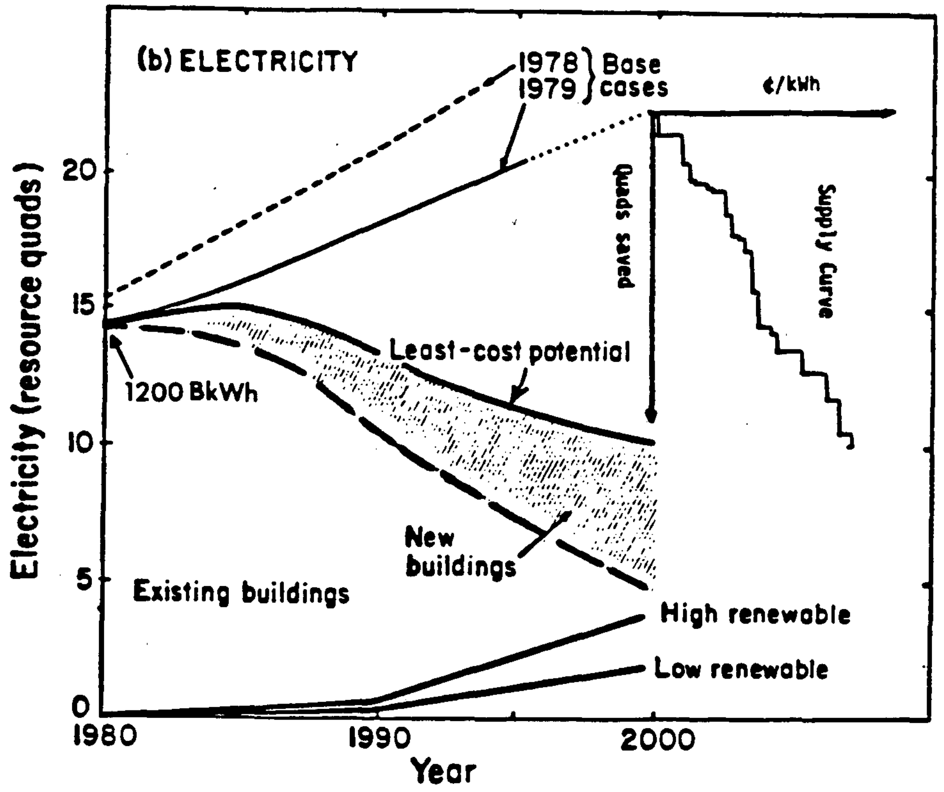

Fig. 17. Projection and potential for U.S. electricity consumption in 2000 A.D., and how they are joined by a supply curve of conserved energy, shown in figure 16. Source: SERI Report.

We want to close the loop, for the residential sector, by relating the supply curves of Fig. 16 to the time series of Fig. 3. (For the moment, pretend that the grand supply curves already include the commercial building options to be discussed in a later chapter.) *Figure 17* shows how the x-axis (energy saved) of the grand supply curve points downwards from the base case, for the appropriate year. (Remember that the supply curves of Fig. 16 apply to 2000 AD.) The "potential" then corresponds to the savings at which the supply curves cross today's price of energy. Remember, for new homes we used a 3% real discount rate (in constant dollars); for retrofit and appliances we used a 10% real discount rate. For the commercial sector the facts are generally the same, except that we shall use a discount rate of 10% real. But if the reader prefers other discount rates, he can now easily replot his own time series.

D. Commercial Buildings

Conservation potentials for commercial buildings are just as spectacular as for residences, and are discussed by Rosenfeld and Hafemeister elsewhere in this book.

ACKNOWLEDGMENTS

I want to thank Professor David Hafemeister for many interesting discussions, and both Hafemeister and Rosemary Riley for help with preparing the paper.

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4. A. Meier, J. Wright, and A. Rosenfeld, SUPPLYING ENERGY THROUGH GREATER EFFICIENCY, University of California Press, Berkeley, 1983.

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6. L. Schipper, A. Ketoff and A. Kahane, Annual Reviews of Energy 10 (1985).

NOTES

a. $85 B is just half of $165 B (1984 $) used by today's stock. By 2000 AD our 85 million homes will grow to 110 million, our 50 billion sq. ft. of commercial floor space will grow to 70 billion, and our 25 quads of resource energy for buildings is forecast to grow to 32 (see Fig. 3), costing $200 B even at today's prices. So, a 50% savings swells to $100 B/year.

b. For a compilation of superinsulated homes, see BECA-A, ref. 2. The R-value is the thermal Resistance measured in English units, i.e., $[\text{Btu ft}^{-2}\ \text{hr}^{-1}\ {}^{o}\text{F}^{-1}]^{-1}$. R-1 converted to SI (Systeme Internationale) is $[0.176\ \text{Watt m}^{-2}\ \text{K}^{-1}]^{-1}$.

c. Mbod = Million barrels of oil equivalent per day.
1 Mbod = 2.12 x 10^{15} Btu/year = 2.12 annual "quads."

d. For an average 1985 U.S. household using gas for heating both space and water; average U.S. annual electric use is: a/c, 1200 kWh (includes homes with no a/c); refrigerator + freezer, 1800; lighting, 1000; misc., 700; Total, 4700. In addition, electric cooking uses 1000 kWh, but the electric saturation of cooking is only 60%, and drying uses 1000 (sat. = 50%). Source: J. McMahon, LBL Residential Model.

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