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ABSTRACT

BECA-B assesses the technical performance and economics of energy conservation retrofit measures. The data collected thus far represent measured energy savings and retrofit costs for over 65 North American residential retrofit projects. The sample size within each project ranges from individual homes to 33,000 dwellings participating in a utility-sponsored program. The median value of space heating energy savings is 24% of the pre- retrofit consumption. For fuel-heated homes, the median cost of conserved energy is \$3.66/GJ, substantially less than the U.S. average 1981 prices for purchased energy of \$4.27/GJ for natural gas and \$8.25/GJ for fuel oil. For ten of the eleven electric heat retrofits the cost of conserved electricity is less than the 1981 U.S. average price of 6.2¢/kWh.

TABLE OF CONTENTS

I. INTRODUCTION

Policy-makers, homeowners, utilities, and contractors have expressed great interest in knowing what fraction of residential energy use can be saved by retrofitting homes. Yet few measurements have been made of the energy savings that are actually attributable to retrofits. Many audits of residential buildings have been performed, but typically yield only estimates of energy-saving potential. Homeowners are often skeptical of these predictions. BECA-B is a compilation and analysis of measured energy use by U.S. and Canadian houses before and after conservation retrofits.* We believe that an ongoing data base developed from metered consumption data can help homeowners and policymakers choose energy-efficient and cost- effective retrofits.

The U.S. residential sector, comprising 77.5 million dwellings, consumed approximately 17 Exajoules [16 resource Quads] of energy in 1980, accounting for one-fifth of the national total.[1,2] Table I provides a breakdown of residential energy consumption by fuel type and end-use.[3]

Table I. 1977 U.S. Residential energy use by fuel and end-use [1.055 EJ= 1 Quad = 10^{15} Btu; note 1EJ=10^{18}J]]

Fuel	EJ	End-Use	EJ
Natural Gas	5.6	Space Heating	8.1
Electricity[a]	8.2	Water Heating	2.4
Fuel Oil	2.5	Air Conditioning	1.2
Other	0.7	Appliances	3.1
		Lighting and other	2.2
	17.0		17.0

[a]Electricity is reported in resource energy units (12 MJ = 11,500 Btu= 1 kWh sold)

Space heating dominates residential energy demand and, hence, most conservation programs have focused on reducing consumption in this end-use.

Improving the energy efficiency of existing residences is a worthwhile objective, given escalating fuel costs and the long lifetime of the U.S. housing stock. Sixty-five to 75 percent of the houses that will be inhabited in the year 2000 have already been built, based on an annual rate of 1.5 to 2.0% for new construction. In 1980, approximately 63.2 billion dollars were spent on residential energy consumption, amounting to an average expenditure of $815 per U.S. household. [1]

*This study is part of a continuing project that collects and reviews measured data on the energy performance of low-energy new homes (BECA-A), existing "retrofitted" homes (BECA-B), energy-efficient commercial buildings (BECA-C) and validation of computer programs (BECA-V).

Millions of homeowners engage in conservation activities each year. In 1979 alone, 3.4 million U.S. households added attic or roof insulation and 3.9 million households bought storm windows and/or storm doors.[1] In 1980, tax credits amounting to $430 million were claimed by U.S. individuals for energy conservation investments, which corresponds to an investment of almost $3 billion per year.[4] Yet, we had some difficulty in finding 69 samples with measured energy savings, though many new evaluation studies are now in progress. Even where building energy use data are available, information on the share of energy savings that is attributable to various retrofit measures is seldom known.

An objective of this study is to better understand the technical performance of residential retrofit measures and evaluate their relative cost-effectiveness. Another goal is to examine the range of conservation savings and costs in order to identify technical and institutional factors associated with high or low levels of performance. Energy engineering techniques will also be evaluated by comparing actual energy savings with predicted savings. Finally, we want to promote the exchange of documented conservation results and the collection and analysis of high quality data. We plan to periodically update this study and invite contributions from all interested parties.

II. DATA SOURCES

The data we seek from each source include: building type and characteristics, project sponsor, sample size, retrofit description and cost, annual energy consumption by fuel type before and after retrofit, local energy price, and year of retrofit. We then calculate energy savings, percent reduction in consumption, cost/m^2, simple payback period, cost of conserved energy, and indicators of building energy performance.

Appendix A summarizes the results from data sources. We have classified the retrofit projects into four general categories based on sponsor: 1) research studies, 2) utility-sponsored programs, 3) building energy services provided by private firms, and 4) government-sponsored programs. Characteristic features of retrofit programs from respective sponsor categories are discussed below.

Research studies

Experiments sponsored by universities and national laboratories (Princeton University, the National Bureau of Standards, and Lawrence Berkeley Laboratory) account for most of our research studies although private firms, such as Johns-Manville, have also participated in research projects. [5-7] Research studies typically make extensive efforts to control for experimental variables. For example, the heating and hot water systems are often sub-metered and a control group is employed as part of the experimental design. Additionally, occupant behavior is monitored. In some cases, the houses are unoccupied (Bowman House), or the researchers operate the building (i.e., open doors and windows periodically) to simulate "standard" occupant behavior. In other instances, occupants are instructed to record behavior that may affect the building's energy performance (i.e., thermostat setting, hours at home, appliance use). In these studies, sample size is small and the analysis of the data tends to be extensive.

Utility-sponsored programs

In the mid-1970's, a number of utilities started offering residential energy audits to their customers. In some cases, the utilities coupled these programs with an offer of low- or zero-interest financing on retrofit projects. In the early stages, these programs were typically concerned with low-cost/no-cost measures (e.g. wrapping water heater tanks) and/or installing attic insulation. In recent years, some utilities have broadened their residential conservation programs to provide financing for complete weatherization packages. The data we have obtained from utility companies come predominantly from three areas of the United States: 1) the Pacific Northwest, 2) the Southeastern portion of the U.S. served by the Tennessee Valley Authority (TVA), and 3) California.

Data on utility-sponsored conservation programs are generally made available on an aggregate basis; that is, measured energy savings are calculated for various retrofit measures that are grouped together as part of a large sample. Often, these studies lack control groups and detailed weather data. The strength of these programs is their ability to reflect energy savings for a rather large fraction of the general population.

Private firms

Many private-sector firms are now entering the potentially large market for retrofit services and products. The single-family housing market appears to be dominated by individual contractors who offer residential energy audits for a fee, often act as installation contractors, and are willing to inspect and warrant their work. Companies entering the multi-family retrofit market, particularly large apartment buildings, often enter into contracts in which they guarantee a specified reduction in energy usage. They take responsibility for building energy management services including operations and maintenance functions and training of maintenance personnel. Their retrofit plan typically emphasizes automatic temperature control, the replacement, repair or alteration of the HVAC system, and lighting load management. Companies such as Scallop Thermal Management, a Shell Oil subsidiary, have provided us with summary reports detailing their retrofit experience in three large apartment buildings, but we have had difficulty finding additional data sources.[8]

Government programs

U.S. agencies or programs that have provided data sources include: 1) Federal Power Marketing Authorities 2) the DOE Low-Income Weatherization Assistance Program and 3) the CSA/NBS Weatherization Research Demonstration Project.

Federal Power Marketing Authorities. A number of Federal Power Marketing Authorities, particularly the Tennessee Valley Authority (TVA) and the Bonneville Power Administration (BPA), have launched ambitious residential conservation programs to reduce the demand for electric power and improve the efficiency of energy use in residences. The data base includes data from TVA's Home Insulation Program and BPA's Midway Energy Conservation Study. [9-11]

Low-Income Weatherization Assistance Program. Nearly 750,000 low-income homes have been weatherized under the initial direction of the Community Services Administration (CSA) and most recently under the auspices of the Department of Energy (DOE). Thousands of local community action agencies have been involved in this effort.

While the program has been extensively implemented, its decentralization has complicated evaluation efforts. The reliability of the data from the Weatherization Program evaluations varies considerably. [12,13]

The studies typically lack a control group, have mixed heating fuel sources within a sample, variations in the quality of workmanship, and inconsistencies in either energy or cost data. Despite these problems, the Low-Income Weatherization Program represents a significant fraction of U.S. investment in residential conservation and focuses on a housing sector where potential increases in energy efficiency are great.

CSA/NBS Weatherization Demonstration Research Project. The Community Services Administration, with technical support provided by the National Bureau of Standards, conducted a national research and demonstration project to determine the energy savings that could be expected from optimally weatherizing low-income homes. [14] The demonstration project entailed extensive retrofitting of homes with close monitoring of cost and energy consumption data. Although the sample houses were fairly typical of low-income housing in terms of size, their pre-retrofit physical condition and maintenance level were better than normally found in low-income residences. Energy savings and retrofit costs were carefully compiled on 142 houses in 12 different locations.

Representativeness of Sample

This compilation is not a representative survey of either the U.S. residential housing stock or the actual portion of the stock that has been retrofitted in the last several years. Our data are taken from evaluation case studies of conservation programs and retrofit projects, reflective of a stratified survey. It is useful to compare characteristic features of our data base with results obtained from the Energy Information Administration's Residential Energy Consumption Survey (RECS), the most comprehensive representative survey on the scope of retrofitting in the residential sector.

We observe that our survey has a disproportionately high number of low income samples (26/69), comprising 38 percent of the data points (excluding controls) compared to RECS data which find that "poor" households are responsible for 11 percent of retrofit activity.

We also note that our study differs markedly from RECS data in terms of housing unit characteristics and location. RECS estimates that 10.6 of 77.5 million households reside in buildings with five or more units, yet we have results from only 3 multi-family retrofit projects. We also have little data from the Northeast region, 7 sources or 10% (excluding New Jersey), a region which has 22% of the households.[1] In future versions, we will analyze in more detail how closely the BECA-B data base resembles the U.S. stock of retrofitted residences.

III. METHODOLOGY

A. Adjustment of Energy Data

The basic information needed to analyze residential energy consumption for space heating includes: space heating or total fuel usage per day (or month, year) before and after retrofit; energy use for purposes other than space heating (the "baseload" usage) for the same time periods; the number of heating degree-days during each time period; and the "normal" (30-year mean) value of monthly and annual heating degree-days (HDD's).

The two major data adjustments of interest are subtraction of the baseload usage and correction of consumption data for the effects of weather in different years. We do not account for any possible changes in the amount of "free" heat (e.g. solar gains, appliance usage) nor separate out the effects of occupant behavior or management. However, where there is a known change in occupants, the home is eliminated from the data set.

Under ideal research conditions, the fuel consumption for space heating is submetered. In our sample,though, most data sources meter only total energy use. In some cases, the contributors estimate and subtract baseload usage, using either a linear regression analysis or the fuel usage during the summer months as the baseload. In cases where no baseload correction is made by the data source, we subtract approximate baseloads using specific regional information obtained from either the All-Electric Homes Study or the Gas Househeating Survey.[15,16]

Weather-related adjustments to the space heating data are also made. In many cases the metered fuel use data are scaled by the number of HDD's (base 18.3^{o}C=65^{o}F) during the measurement period and then consumption is normalized to a "standard" year using the 30-year mean value of HDD's for that site. For data sets with more extensive consumption and weather data, a reference (or balance point) temperature is determined. Energy consumption for a "standard" year is calculated using the number of HDD's to the base temperature equal to the reference temperature.

Princeton University researchers utilize another weather-correction method. In their projects, the <u>total</u> consumption of space heating fuel (includes all uses for the fuel) is regressed against the corresponding degree days based on a variety of reference temperatures. The reference temperature selected is the one that gives the regression with the best least-squares fit. Also determined in this procedure are two parameters that characterize the heating and baseload components. These parameters, together with the normal-year degree days to the best-fit reference temperature, are used to calculate a weather-normalized annual consumption (NAC).[17]

We assign each of our samples a confidence-level ranking (A, B, C, D, F) shown in Column Q, Appendix A. The only data we include are those with a confidence level of "C" or better. A critical assessment is made of such factors as the method used to separate the space heating component from total energy use, the weather-correction method, and the accuracy of retrofit cost data. No retrofit data are included unless they are linked to actual measured energy consumption.

B. Economic Analysis

The basic investment framework for conservation measures involves an initial outlay of capital resulting in future reductions in energy use and dollar savings. Two indicators are used to evaluate the conservation investment, cost of conserved energy (CCE) and simple payback time (SPT). Both have the advantage of avoiding the need to guess future energy prices yet are conservative indices of cost- effectiveness if energy prices are assumed to increase faster than general inflation.

Simple payback time is the period required for the undiscounted value of the future energy savings (at today's prices) to equal the original investment. It can be expressed as

$$SPT = \frac{C_I}{D_s} = \frac{C_I}{E_s \times P} \qquad (1)$$

where C_I is the initial cost of the conservation investment,
D_s is annual dollar savings,
E_s is annual energy savings,
P is the local energy price the winter after retrofit.

The cost of conserved energy is found by dividing the annualized cost of the retrofit by the annual energy savings due to the investment. A conservation measure is economically attractive if its cost of conserved energy (CCE) is less than the price of purchased energy (P).[18] For the homeowner, P can be defined as the average price of energy but for a utility it is the marginal (avoided) cost of supplying energy from new sources (in the simplest cases). CCE can be expressed as:

$$CCE = \frac{(C_I + M) \times (CRR)}{E_s} \qquad (2)$$

where C_I is contractor cost of original investment,
M is the present value of maintenance costs over the measure's physical lifetime,
CRR is the capital recovery rate,
E_s is the annual energy savings.

We convert the one-time investment to an annual cost by computing a capital recovery rate (CRR). The formula for the capital recovery rate is:

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

where d is the discount rate, and
n is the physical lifetime of the measure.
The cost of conserved energy requires the incorporation of methods used in life-cycle costing.* We estimate a useful lifetime for typical conservation retrofit measures in our sample homes and find a weighted average of 15-20 years. To account for maintenance and replacement costs, we round this average lifetime down to 15 years and eliminate the explicit maintenance cost factor in Equation 2, except in cases of retrofitting of large apartment complexes.

In the equation for CRR, the discount rate is expressed in real (constant) rather than nominal (inflated) dollars. We use real discount rates to avoid assumptions about future inflation. For purposes of sensitivity analysis, we calculate CCE using three different real discount rates (3,7, and 10%) in the capital recovery rate formula (Col. M1, M2, and M3 in Appendix A) but the figures reflect only the middle value (CRR=.110, based on a 7% discount rate for 15 year amortization period).

The lowest real discount rate, 3% per year, typically applies to secured, long-term loans, such as new home mortgages (which averaged 2.29% (real) in the U.S. for the period 1961-1979).[19] The highest real discount rate (10% per annum) is used for riskier and generally short-term loans made in the private sector (i.e. second trust deeds, appliances, or used car loans). Many U.S. government programs use this rate in their cost-benefit analysis. The Energy Security Act of 1980 specifies that U.S. government conservation and solar applications' investments be evaluated using a 7% real discount rate.[20]

The CCE values are expressed in 1981 constant dollars. We convert all original retrofit costs into 1981 dollars, using the Gross National Product Implicit Price Deflators, in order to provide a comparable basis for evaluating the relative cost-effectiveness of retrofit projects undertaken in different years.

C. Adjustment of Cost Data

We are interested in the direct costs to the homeowner of contractor-installed retrofit measures. If the retrofit is accomplished as part of a research study, we use the researchers' best estimate of the equivalent contractor's cost (materials, labor, overhead, and profit). If the conservation measures are installed as part of a utility loan program, we interpret the retrofit cost as being equal to the loan amount.** Most utility administrative overhead costs are excluded since they are not direct costs to the homeowner, but are paid by all

*We have not considered the impact of tax credits or calculated a salvage cost.

**An exception to this practice is made for cost data from utility programs which indicate that the loan amounts are "bumping up" against program maximums. In these cases, we attempt to determine the additional investment outlay provided by the homeowner for the retrofits.

ratepayers. For government-sponsored weatherization programs we follow the procedure of a DOE-commissioned study which estimated that materials, labor, and contractor overhead costs contributed roughly equally to overall costs.[13] On this basis, if only materials costs are available, then total costs are taken to be three times the price of materials. An estimate of the market cost of performing the weatherization work is obtained by using this multiplicative factor. The errors from this cost adjustment procedure would likely tend to overstate the cost of conservation measures. For example, in cases where a homeowner contributes all the labor for a retrofit, total costs would actually be lower than our estimate, as would the estimated cost of conserved energy.

D. Units for Electricity: Use of Resource Energy

Some of our sample homes are heated by fuel, others by electricity. We want to evaluate energy savings on a comparable economic basis regardless of fuel type. One approach is to evaluate electricity in terms of the heat energy produced "at the building site," by an electric-resistance appliance i.e., 3.6 MJ/kWh [3413 Btu per kWh]. The advantage of using "site electricity" units for comparing fuel-heated and electrically-heated buildings is that this indicates the buildings' physical performance (heat load to be met). A disadvantage is that measuring electricity in terms of site energy fails to account for the substantial fuel use required off-site to generate electricity.

Resource electricity units account for the total fuel required by a utility system to generate and deliver a high grade energy source, electricity. The resource conversion factor is 12 MJ per kWh [11,500 Btu per kWh], which reflects typical power plant efficiency (33%) and transmission losses (about 10%). We choose to use resource electricity units because the costs per joule for fuel and electricity end up roughly equivalent (See Appendix B for details).

We do <u>not</u>, however, use resource energy units in calculating the fuel integrity of electrically-heated homes (see Appendix A, Column P). In this case, we are evaluating the pre- and post-retrofit performances of the building shell and heating system rather than the relative primary energy savings of various retrofits. The conventional practice used by building scientists is to express fuel requirements in terms of site energy. For fuel-heated homes, we tabulate the fuel use per m^2 per heating degree-day. For electric heat it is then necessary to adjust for differences in the seasonal furnace efficiencies of gas-and-oil heated homes vs. electrically-heated homes. We calculate how much fuel an all-electric house would use if it had been heated by a gas or oil furnace whose typical seasonal efficiency was 0.67. Thus the equivalent fuel usage is then 3.6 MJ $\div$ 0.67, or 5.4 MJ/kWh [5120 Btu/kwh], the conversion constant used for electrically-heated homes in Appendix A, Column P.

E. Control Group Savings

Control groups are used in many of the retrofit projects. Interpretation of energy use data for a control group depends on the objective of the study. Subtraction of control group savings is appropriate if the objective is to measure program-specific effects; for example, the energy savings attributable to a utility conservation program beyond what would otherwise have occurred. Our focus is on measured data that show the technical performance and cost-effectiveness of conservation retrofits. We have only a secondary interest in the extent to which a specific program or regulation--as opposed to "market responses" to rising energy costs--actualy triggered the decision to retrofit a building. Thus we list control group energy savings in the Summary Data Table, but most of our figures reflect gross rather than net energy savings for each data point.

IV. TYPES OF RETROFIT MEASURES

Most residential conservation measures at present are aimed at improving energy efficiency in two end-use areas: space heating and cooling, and domestic water heating.

Space Heating and Cooling

Most retrofit measures designed to reduce heating and cooling energy use consist of tightening the buildings' thermal envelope. We have very little data on the effect of residential retrofits on energy consumed by cooling systems. Thus, our economic calculations are conservative since they credit only energy savings from heating systems. In many instances, the retrofits also result in cooling savings.

The most popular retrofit measure in the data base is the addition of ceiling insulation. This measure effects dramatic savings in dwellings that have uninsulated attics. Substantial savings are also realized in cold climates if the "before" level of ceiling insulation is RSI-1.3-1.9 [R-7 or R-11].

In cold climates, the installation of storm windows and/or storm doors is another common conservation measure, a measure undertaken by one-third of the data sources. The installation of a clock thermostat or modifications to an existing heating system (i.e. installation of flue dampers) were made by 10% of the data sources. In larger multi-family buildings, replacement or adjustment of the HVAC system and automatic energy control systems were the most common retrofits. We have data on only one architectural improvement, a passive solar wall retrofit, but hope to identify more retrofits of this type in the future.

Caulking and weatherstripping are very common retrofit measures to cut down on infiltration in a house. This measure has been implemented by almost one-half of our data sources, particlarly in low-income housing. A relatively new technique for the discovery of less obvious heat loss paths has been developed by researchers at Princeton and LBL. This technique involves pressurizing a home using a blower door. Heat leakage paths and thermal "bypasses" are identified with the aid of smoke sticks and an infrared camera. Major leakage sites are then sealed.

Domestic Hot Water

The average U.S. home uses about 32 GJ [30 MBtu or 300 therms] per year to heat water for domestic use. Potentially large savings are possible in this area. At present, wrapping an insulating blanket around a water heater tank is the the most popular retrofit measure. Several utilities in the northwestern part of the United States have been wrapping their customers' water heaters for several years at no charge. They estimate annual energy savings of approximately 500 kWh (worth $30 at 6¢/kWh) are realized at a cost of $15 to $20, an excellent return on investment. Other common retrofit measures include wrapping the hot water distribution pipes near the heater, lowering the thermostat setting of the water heater, and installing low-flow shower heads and water heater flue dampers. Although we have not attempted to assess savings from active or passive solar hot water systems, they are another increasingly popular residential retrofit.

V. RESULTS

Energy Savings

Annual resource energy savings as a function of the contractor cost of the retrofit are shown in Figure 1. We observe the expected trend of increased savings for larger investment, but the data are widely scattered. For retrofit costs equal to or less than $2000, annual energy savings varies up to a factor of seven. In our sample, there is a wide range in the cost-effectiveness of retrofit measures. The median value of energy savings is 29.5 GJ [28 MBtu]; the median cost is $1082.

In Fig. 1, the sloping reference lines represent prices of purchased energy. A conservation retrofit is cost-effective if the data point lies above the price line for that fuel. Nine of the 11 electrically heated homes lie on or above the 5¢/kWh reference line and 27 of the 37 gas-heated homes have energy savings above the $4.74/GJ [50¢/therm] reference line. The reference price lines are close to the 1981 U.S. average residential prices - gas at $4.27/GJ [45¢/therm] and electricity at 6.2¢/kWh.* [21]

In Figure 2, the percent savings of space heating energy is plotted against the contractor cost of the retrofit. The spread in results narrows slightly compared to Fig. 1 but there is still considerable scatter. We fit the data using a two-parameter function of the form

$$y = a(1-e^{-bx}). \tag{4}$$

While the fit has a poor correlation coefficient (r^2=.32), we present the curved line to guide the reader's eye to the asymptotic relationship between contractor cost and percent savings. The data reflect a crude law of diminishing marginal returns with increasing investment. The data suggest that investments up to $1000 in conservation retrofits, on the average, reduce a house's space heating energy consumption up to 20-25%; investments up to $2000 reduce annual consumption up to 35-40%. In Figure 3, a histogram of the retrofit results expressed in percent savings of space heating energy is presented. The median value is found to be 24% of the pre-retrofit consumption.

Range of Savings

An objective of the BECA project is to indicate factors associated with high or low levels of savings and cost effectiveness. Those retrofits that have the highest and lowest ratio of energy saved per dollar invested are discussed briefly.

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* Note, however, that there are regional variations in the price of gas and electricity, so that cost-effectiveness of individual retrofit projects may be different from that indicated here.

In Fig. 1, the data point labeled OA2.1 represents the Page Homes project, a 1950's style multi-family public housing complex in New Jersey that is retrofitted with a micro-computer-based boiler control system. The system, designed by Bumblebee Energy Management System, consists of indoor temperature sensors located in one-third of the apartments. The sensors transmit periodic readings to a micro-processor. Using this information, the computer adjusts the hot water temperature for the boiler/heater system. The average apartment temperature has been lowered from a pre-retrofit average of 28°C [82°F] to 24°C [75°F] during the day, and 23°C [73°F] at night. Other energy management measures were also taken, including improved operation and maintenance (saving approximately 10-15% of the total) and rebalancing of the hot water radiators.

Prior to the retrofit, annual energy consumption per apartment was 3410 liters of fuel oil which in the post-retrofit period has been reduced to 1740 liters. [22] The pre-retrofit energy consumption of this building complex is comparable to that of other buildings operated by the housing authority yet it would be considered an "energy guzzler" in comparison to the overall residential housing stock. The pre-retrofit fuel integrity for Page Homes is 482 KJ/m^2-DD_C [23.6 Btu/ft^2-DD_F], far higher than the U.S. average of 260 KJ/m^2-DD_C [12.7 Btu/ft^2-DD_F] for single-family residences.[23] EIA surveys show that heating energy use in oil-heated multi-family housing units is comparable to or larger than that in single family homes. [24] This successful retrofit suggests that substantial savings may be possible by installing improved heating control systems, even without changes to the building shell, in some large multi-family apartment buildings.

Conservation programs that were sponsored by TVA and Puget Power (points E1.1, E1.2, and E6 respectively) also achieve high energy savings (50-84 GJ) relative to cost ($200-1300). Historically, low priority has been given to energy-efficient design in homes located in these regions, as the Pacific Northwest and the Southeast have relied on cheap hydroelectric power. Most homes were uninsulated and "leaky," thus allowing for significant improvements in building thermal performance at relatively low cost. Savings from these programs are impressive, especially given the large sample sizes (8802 homes in the case of Puget Power).[9,10] [25]

The DOE Low Income Weatherization Program in Minnesota is an example of a project with relatively poor results, (plotted as data points M10.1 and M10.3). Annual energy savings of only 11.9 GJ (10%) and 7.3 GJ (7%) were achieved for retrofits estimated to cost $1000-1100.[26] The poor benefit-cost ratio could be attributable either to poor workmanship (the project relied on "free" CETA labor), our possible overestimate of equivalent contractor costs, or diminishing returns on investment in homes with moderately low initial fuel integrity values.

Points G15 and M2 also represent low-income weatherization experiments, conducted in this case by the CSA/NBS Demonstration Program. The overall 12-city experiment achieved annual space heating energy savings of 31% in the aggregate and proved to be cost-effective. However, at several of the sites, there were problems with the quality of retrofit work and data collection procedures. In St. Louis (G15), post-retrofit inspection of the homes revealed that several storm windows were missing. When the bills for materials were examined by project technical staff, they discovered that it was physically impossible to install the amount of insulation claimed, given the buildings' measured dimensions. Although these data errors were corrected insofar as possible, the low savings in St. Louis were likely the result of poor workmanship. In Atlanta (M2), mechanical retrofit options (which yielded the highest dollar savings overall in the CSA/NBS project) never were installed due to poor communication.[14] Those points show annual savings of only 15-18 GJ for investments of $1400-2000, and are not cost-effective. All low-income weatherization retrofit projects that report low energy savings with relatively high costs installed caulking and weatherstripping: measures whose energy savings are likely to be small and whose effectiveness is greatly impacted by the quality of workmanship.[27]

Subtraction of Control Group Savings

Figure 4 illustrates the reduction in "program-induced" energy savings when control group results are considered. For example, data point E5.1 shows the measured savings, 50.6 GJ (resource units), from Seattle City Light's Residential Insulation Program (RIP). During the same period, average consumption per household decreased by 13% in the blind control group.[28] We show an arrow reducing the initial savings observed in point E5.1 by 13% of the pre-retrofit usage (or 27.2 GJ). Thus, the energy savings attributable to the utility's conservation program are 23.4 resource energy GJ or 1930 kWh per household. Similar subtractions are shown in Fig. 4 for nine other data points.

On the average (equal weighting for each site), the 14 active control groups decrease their annual energy usage by 14.4 GJ [13.6 MBtu] or 9.5 percent. Consumption also declines by approximately 8 percent in the 12 blind control groups and utility aggregates. In both cases, these changes probably indicate some combination of "independently" installed retrofit measures, more energy-efficient operation of the home or appliances, and possibly reduced levels of occupant comfort.

Simple Payback Periods

Figure 5 shows the distribution of simple payback periods for the retrofit projects in our compilation. The median payback time is 7.9 years. A factor that partially accounts for the relatively high median value is the large number of research and demonstration projects. In these studies, new retrofit measures or procedures with unproven cost-effectiveness are often tested. The lower median payback time of 5.7 years for conservation programs sponsored by utilities and private firms reflects investments primarily in established retrofit measures or procedures with relatively high returns on investment.

Cost of Conserved Energy

The relationship between contractor cost for the retrofits and the cost of conserved energy is shown in Figure 6. Reference prices of purchased electricity, gas, and oil are drawn as horizontal lines against which conservation retrofits for each fuel type can be compared. Including points that overflow the plotted axes, we find the following results: 72% (28 of 39) of the gas-heat projects have a cost of conserved energy below the reference gas price of $4.74/GJ [50¢/therm], 82% (9 of 11) of the all-electric homes save heating energy more cheaply than the reference electricity price of 5¢/kWh, and 80% (4 of 5) of the oil-heat retrofits lie below a fuel oil price of $8.60/GJ [$1.25/gal].

We observe that most retrofits costing less than $2500 had CCE's below $4.74/GJ [$5/MBtu], a result found in 46 of the 58 samples. Seven less successful retrofits with investments between $500 and $2000 have cost of conserved energy values ranging from $5.20 to $8.50/GJ. For the six data sources with retrofit costs between $2500 and $4400, only one has a CCE of less than $4.74/GJ; the other five CCE's range from $4.74-6.60/GJ. The six least successful projects have CCE's from $10.40-15.20/GJ, and are not shown in this figure as they overflow the vertical scale. Fig. 6 also depicts the cost-effectiveness of "house doctoring" as is evidenced by the cluster of gas-heat data points (from Princeton's Modular Retrofit Experiment) with cost of conserved energy values between $1-2/GJ and retrofit costs of $350.

The distribution of cost of conserved energy values for the sample is shown in Fig. 7. Overall, the median cost of conserved energy is $3.60/GJ [$3.80/MBtu], with the median value for fuel-heated homes at $3.66/GJ and the CCE for electrically-heated homes at 3.1¢/kWh.

In this survey, the reporting of results by data sources is too aggregated to permit ordering individual retrofit options by return on investment. In cases where results can be disaggregated based on submetering, the data suggest that the most cost-effective set of retrofits includes attic insulation and measures that are part of the Princeton/LBL "house doctor" program of instrumented energy analysis and retrofit. At this time, our data indicate a high correlation between low retrofit costs and cost-effective CCE values.

Actual Savings vs Predicted Savings

Millions of energy audits have been performed in U.S. residences for the purpose of estimating retrofit costs and savings to help guide homeowners' decisions on conservation investments. Comparison of actual vs. predicted savings is an important consideration in the evaluation of conservation programs -- an area in which little systematic work has been done. At present, we have limited data on this subject as shown in the following table.

Table II. Comparison of Actual vs. Predicted Energy Savings

Label	Sponsor	No. of Homes	Actual	Predicted	Method
G1	NBS	1	59%	52%	Modified DD
E2	TVA	546	22%	25%	S.S. Heat Loss
E4	PPL	1896	20%	25%	S.S. Heat Loss
E6	Puget	8802	35%	26%	S.S. Heat Loss
E7	PGE	161	32%	33%	S.S. Heat Loss
E8.1	BPA/LBL	5	9%	4%	CIRA
E8.2	BPA/LBL	5	16%	25%	CIRA
E8.3	BPA/LBL	4	42%	36%	CIRA

In four of the above cases, the standard engineering method of making a steady-state heat loss calculation is used to estimate the savings. For one case a modified degree day method (steady state heat losses plus a balance point temperature adjustment) is employed. LBL used its CIRA micro-computer program to predict energy savings in the three-cell Midway project. Predictions for a particular house or group of houses can vary considerably, depending on the method used. In one-half the cases listed in Table II, actual savings fall short of predictions whereas in the other half they exceed the predicted values. We see that the differences between actual and predicted values are not exceedingly large for our sample, all but one of which involves aggregates of houses. Typically, the correlation between actual and predicted usage is poor for an individual house.

We have also collected pre-retrofit predictions of savings on many new conservation programs. Further quantitative analysis is planned on this subject as new projects report their post-retrofit consumption and actual energy savings.

VI. CONCLUSIONS

Results from this study indicate that conservation investments up to $1000 reduce a house's space heating consumption by 20-25 percent, on the average, while investments up to $2000 decrease usage by approximately 35-40 percent. The median value of space heating energy savings for 64 data points is 24 percent of the pre-retrofit usage. One important finding is that on-the-spot retrofits accompanying instrumented energy analysis were, despite the use of high-priced instrumentation, generally less expensive and invariably more cost-effective than other retrofit measures, irrespective of the presence or absence of insulation. These conclusions emerge from large-scale experiments designed by Princeton University (though the retrofits were carried out by others). Preliminary results reveal that attic insulation, sealing bypass and infiltration losses using pressurization and infrared diagnostic techniques, and wrapping hot water heaters with an insulating blanket are cost-effective retrofit measures.

Though the data compilation contains wide variation in the type of homes, the type of fuels, the locations and the type of retrofits, the overall results from aggregating thousands of individual cases show an attractive cost of conserved energy for residential retrofits. The median cost of conserved energy for our data points is an attractive $3.60/GJ [$3.80/MBtu], comfortably less than the 1981 U.S. average residential cost for natural gas ($4.27/GJ) or fuel oil ($8.25/GJ). In fact, 27 of the 39 gas-heat points are below the average residential gas price and 4 of the 5 oil-heat points fall below the price for heating oil. Of the 11 electric heat data points, ten show a cost of conserved electricity of less than 6.2¢/kWh, the 1981 average U.S. price.

The absence of data on multi-family units and on the durability of energy savings from retrofits are worth noting. Thus, future additions to the BECA-B data base will emphasize multi-family retrofit projects and multi-year data on energy savings. We are also interested in obtaining more data on the results of low cost/no cost programs and from "failed" retrofit programs. Data on these subjects will allow us to describe factors that account for successful and "failed" programs and better explain variation in predicted vs. actual energy savings.

Finally, we express the hope that as a result of this paper, potential contributors will contact us to begin sharing data, so that we can greatly increase the scope and representativeness of this compilation.

VII. ACKNOWLEDGEMENTS

A number of persons contributed to this study, and the authors are grateful to all. Tom Borgers and Joe Costello collected some initial data for the 1980 Santa Cruz conference. Richard Crenshaw generously shared data and insight from the 12-city CSA/NBS study. Ender Erdem and Wolfgang Lührsen contributed their computing expertise. Alan Meier and David Grimsrud helped us to interpret the data. Jeff Harris guided us with many helpful suggestions and critical comments. Moya Melody and Laurel Cook helped to edit the paper and Jeana Traynor contributed her word processing skills. We also thank the many colleagues at other institutions who supplied us with data and answered our questions, especially Robert Dumont, at the National Research Center of Canada, who shared his Canadian files with us.

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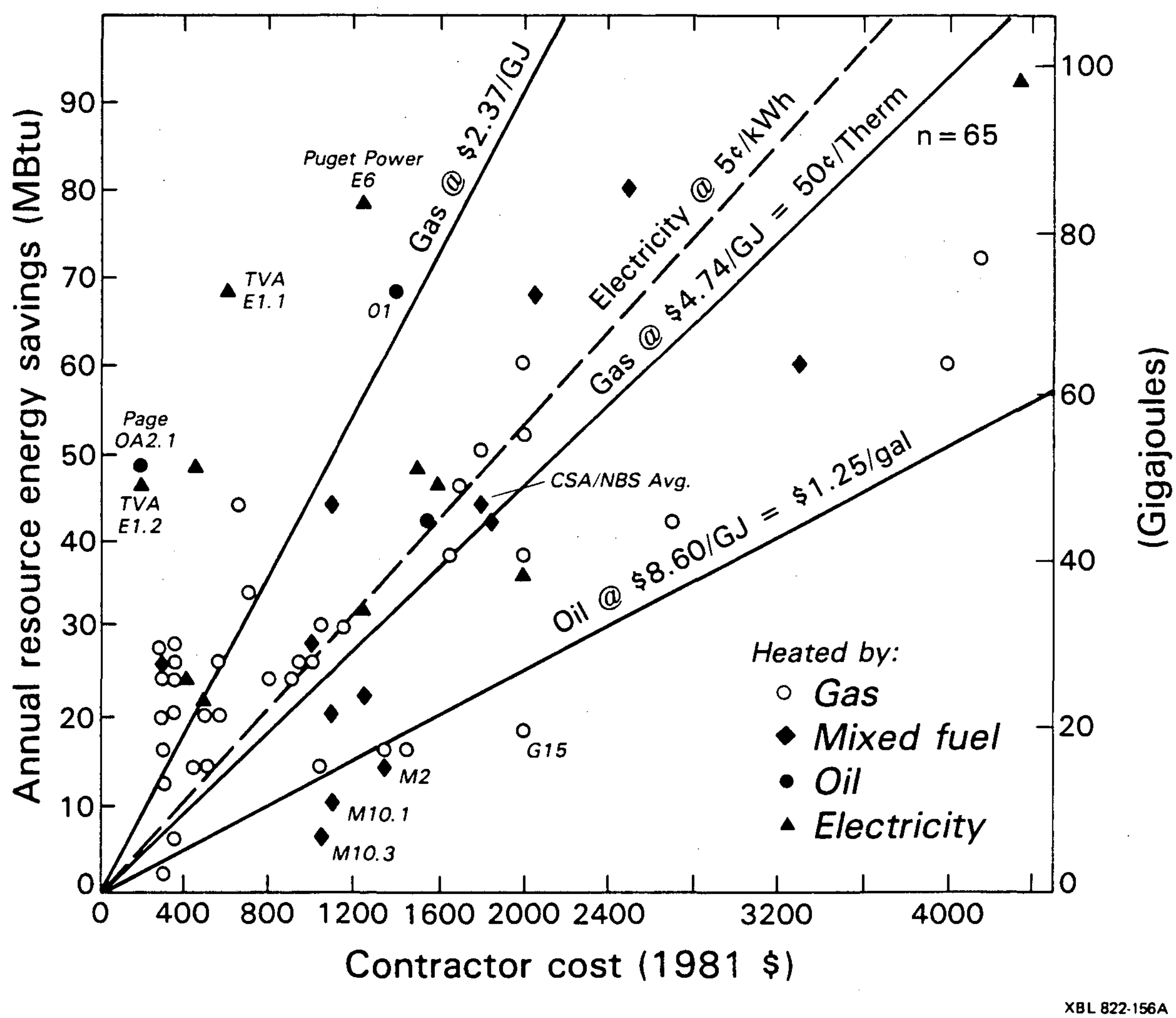
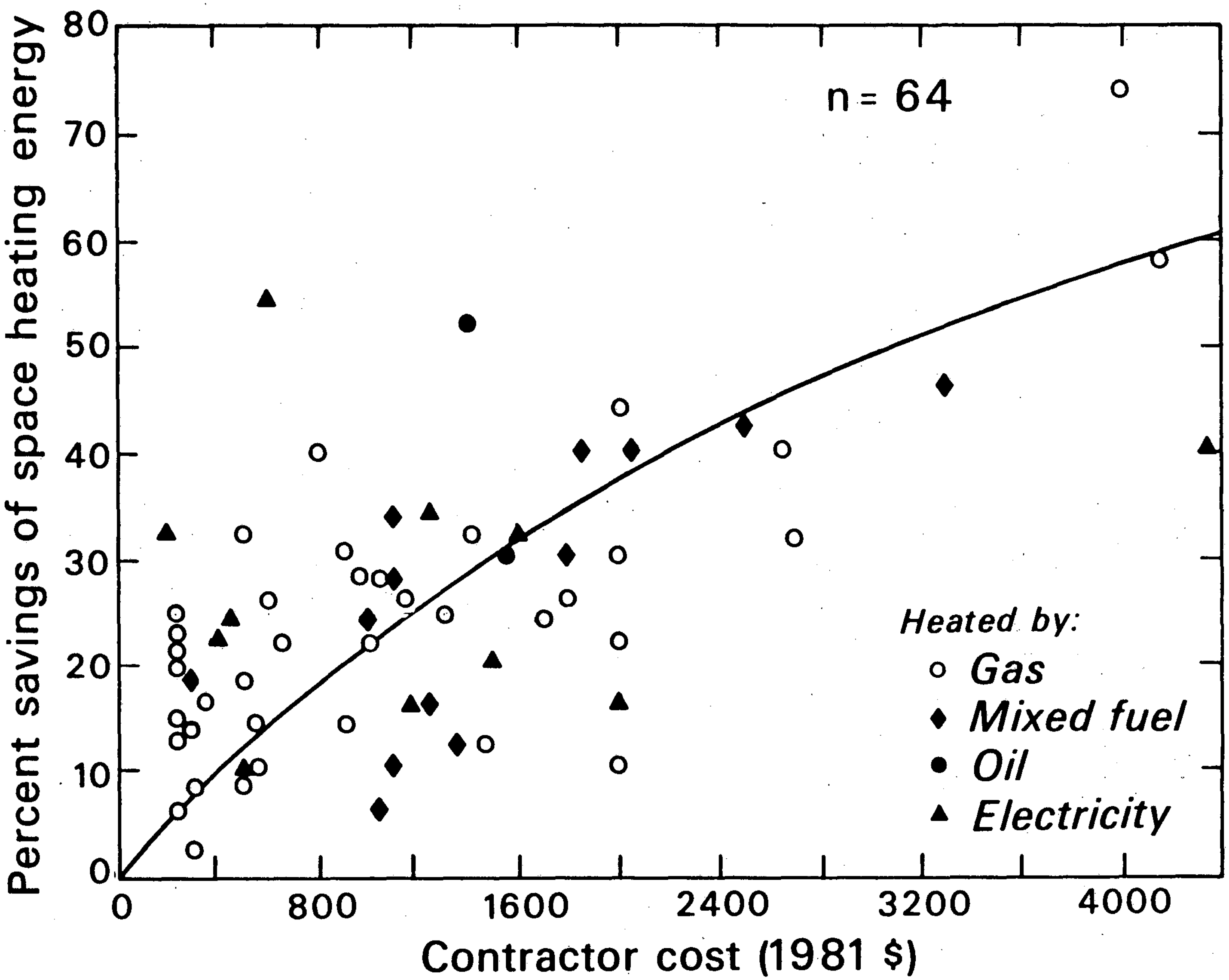


Fig. 1. Annual savings after retrofit are plotted against the contractor cost of retrofits for 65 data sources. The sloping reference lines represent the boundary of cost-effectiveness for typical residential energy prices. Since conservation investments are typically "one-time," the future stream of energy purchases for 15 years is converted to a single present value, assuming a 7% real discount rate. The conservation retrofit is cost-effective if the data point lies above the purchased energy line for that fuel. In most cases the plotted savings apply to space heat only, except for 15 samples which address other end uses in addition to space heating (shown in Appendix A, Col. J as W or F). In those 15 cases, we plot the combined savings. Electricity is measured in resource units of 12.1 MJ per kWh sold. [12.1 MJ = 11,500 Btu]



XBL 822-161

Fig. 2. Percent savings of space heating energy vs. Contractor cost for 64 retrofit projects. The percent savings are taken from column K4 in Appendix A except for the 14 Princeton MRE points which are calculated from the space heating portions (columns P1 and P2) of the total fuel usage. The curved line represents a fit of the data to the equation $y=a(1-e^{-bx})$. The data suggest approximate energy savings of 20-25% for investments up to $1000 and 35-40% for conservation investments up to $2000.

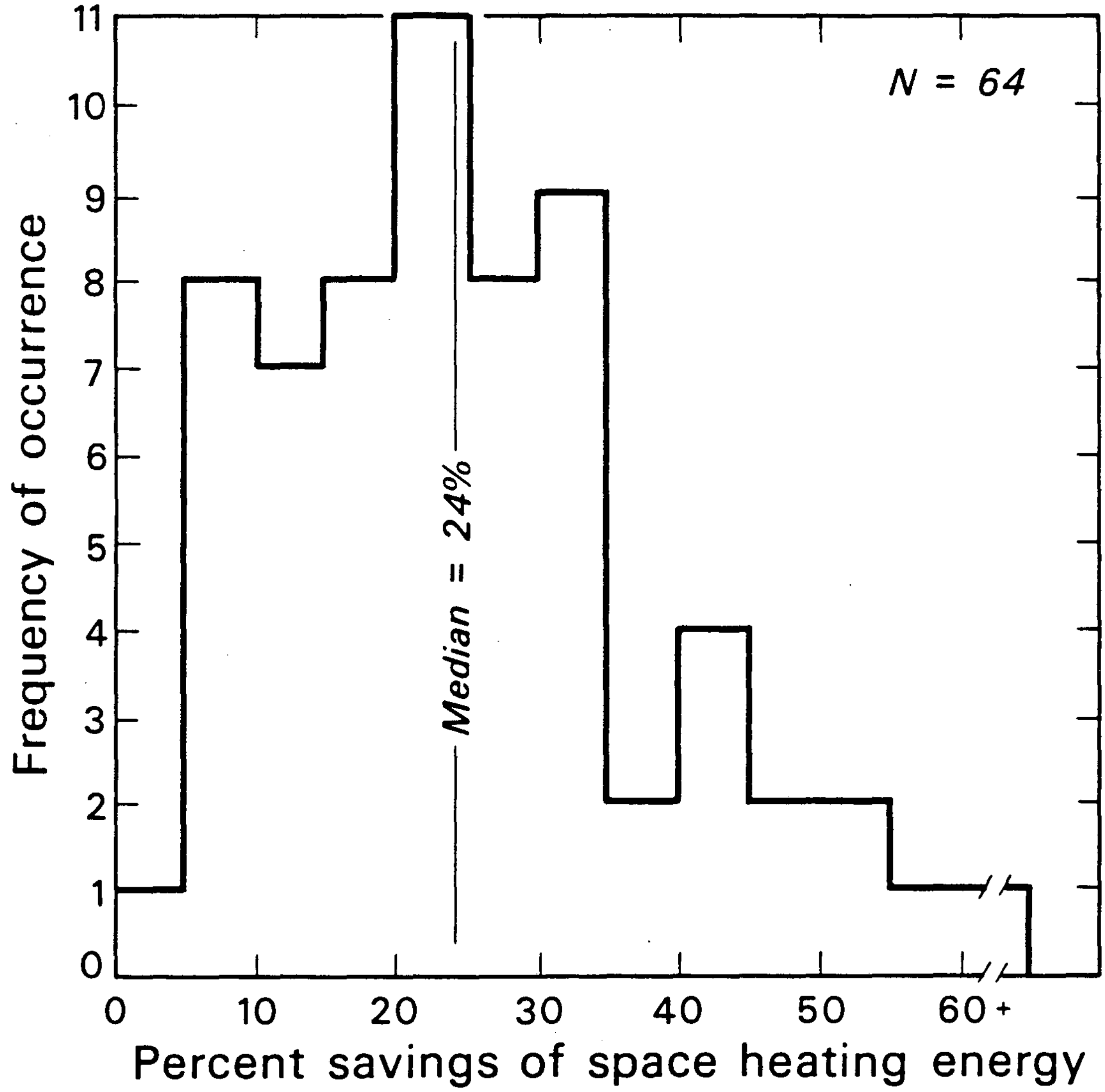


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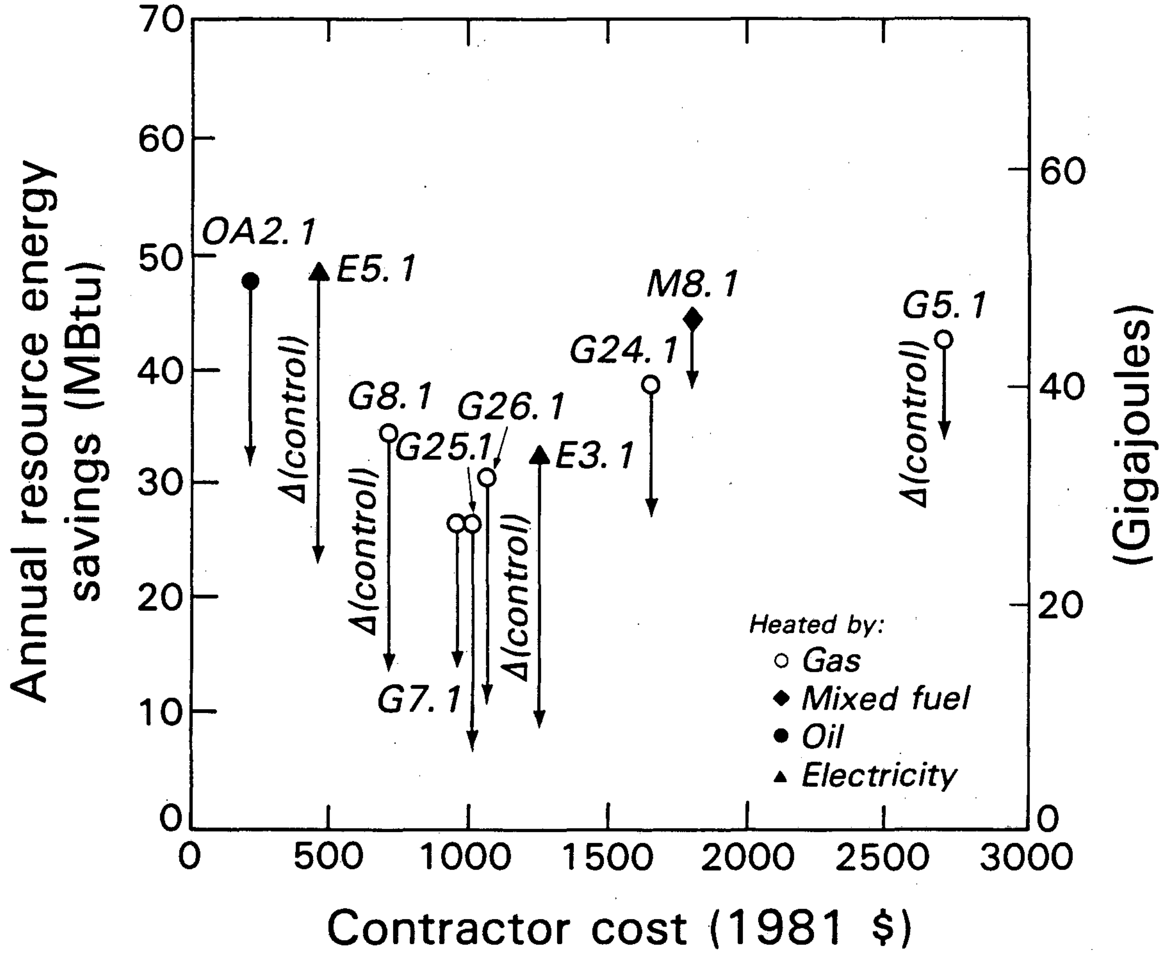
Fig. 3. Histogram of the energy savings data shown in Figure 2. The median value of space heating energy savings is 24% of the pre-retrofit consumption.



XBL 822-155A

Fig. 4. The reduction in "program-induced" savings when control group energy savings are subtracted is shown. The scatter plot illustrates the reduction in savings (drawn from the initial data point by an arrow) for 10 of 24 samples that employ a control group. The points not included either overlap those shown or are active control groups from the individual cities in the CSA/NBS Demonstration Program (whose results are aggregated in M 8.1A).

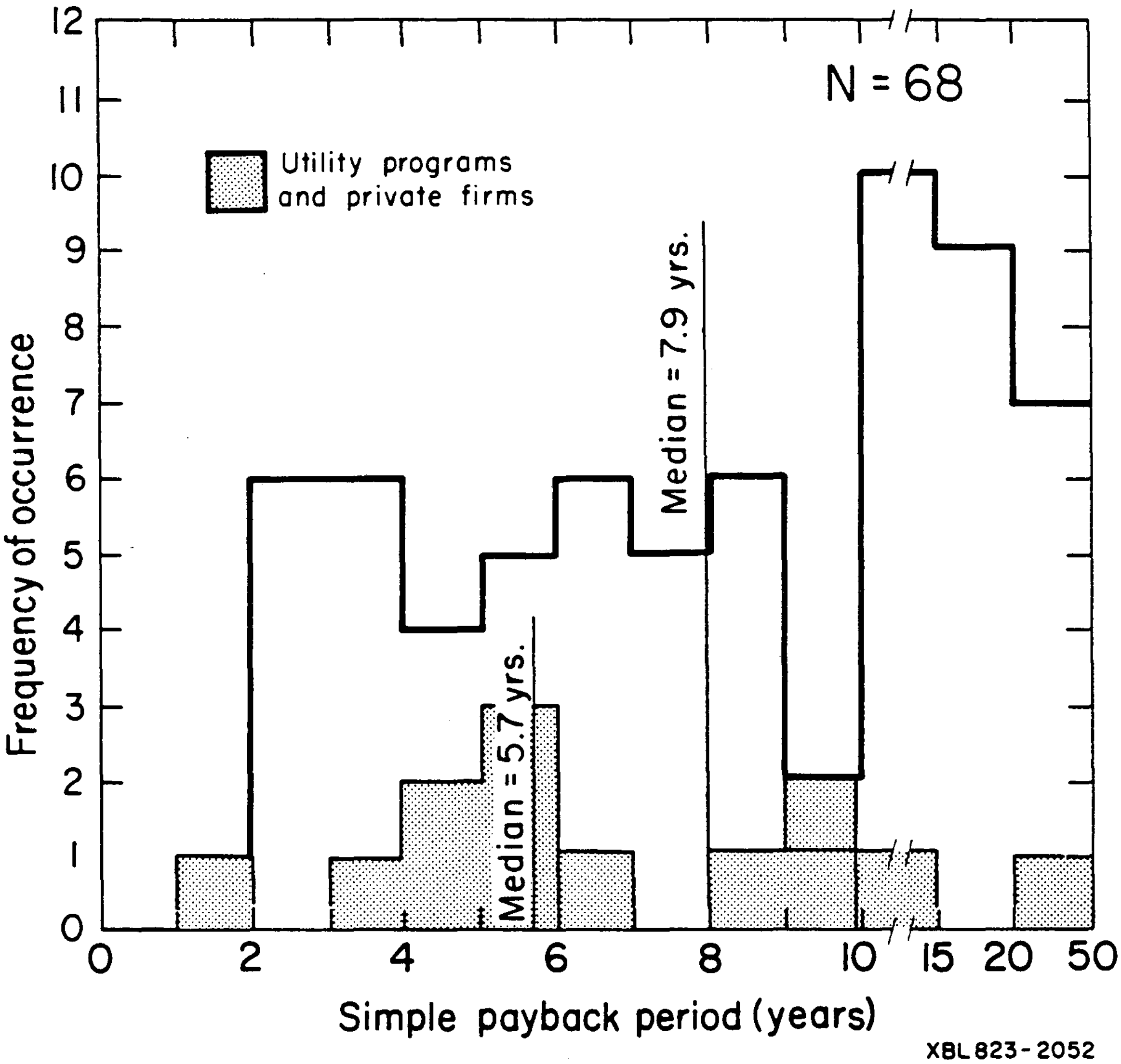


Fig. 5. The simple payback period for 68 retrofit projects is presented. The median payback time is 7.9 years. Results for utility-sponsored programs and private firms are shown in the shaded area. Utility and privately-sponsored conservation programs have a median payback time of 5.7 years.

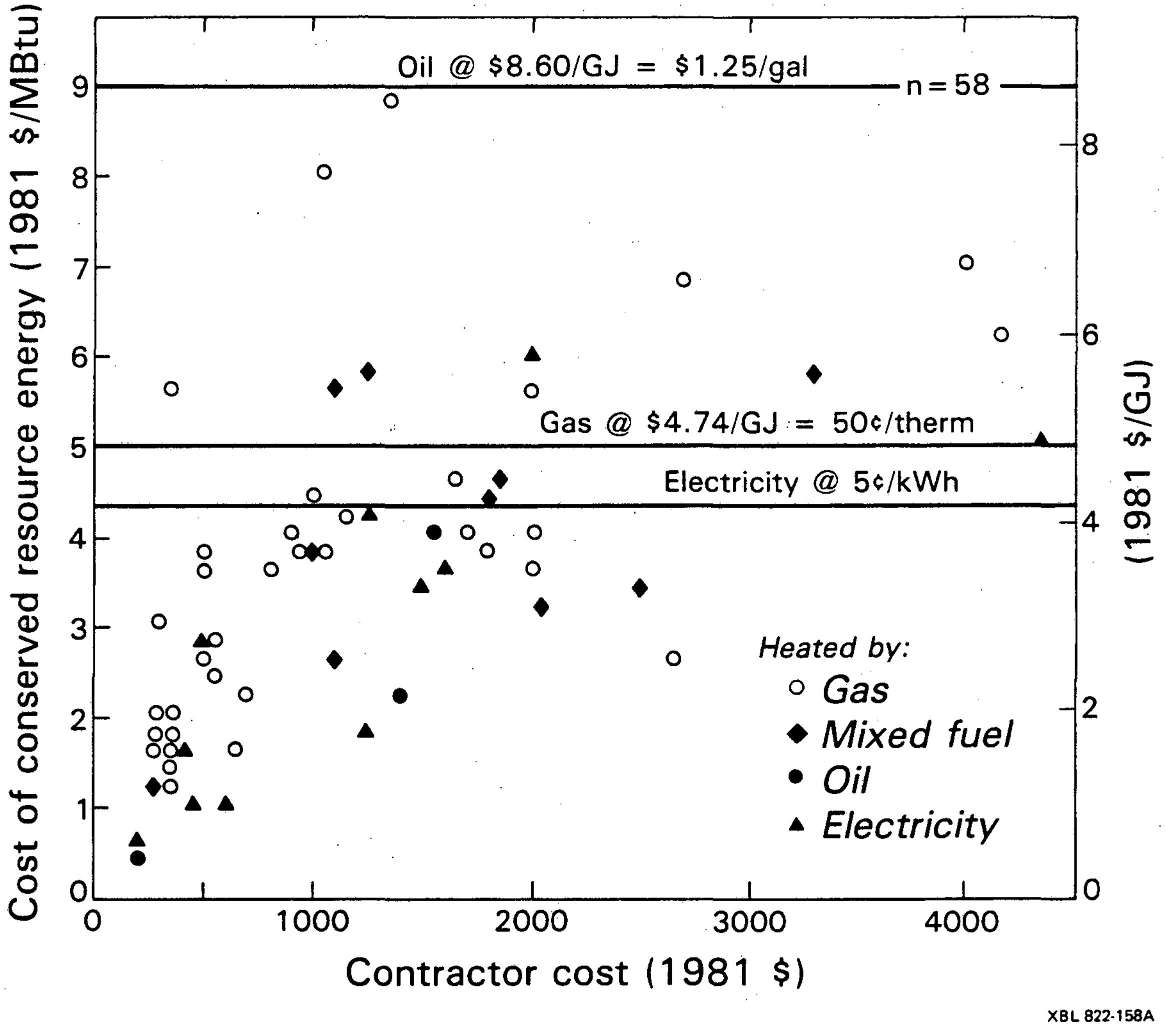


Fig. 6. The scatter plot shows the relationship between the cost of conserved energy and the contractor cost for the measures. The cost of conserved energy equals the ratio, total investment over annual savings, multiplied by the capital recovery factor (.11, assuming a 7% real discount rate and 15-year amortization period). The horizontal lines represent prices of purchased energy against which conservation retrofits should be compared. Of the 58 sources, 46 invested less than $2500 per home, and obtained CCE's of less than $4.74/GJ. The gas data points clustered between $1-2/GJ represent the results of the Princeton house-doctoring experiments.

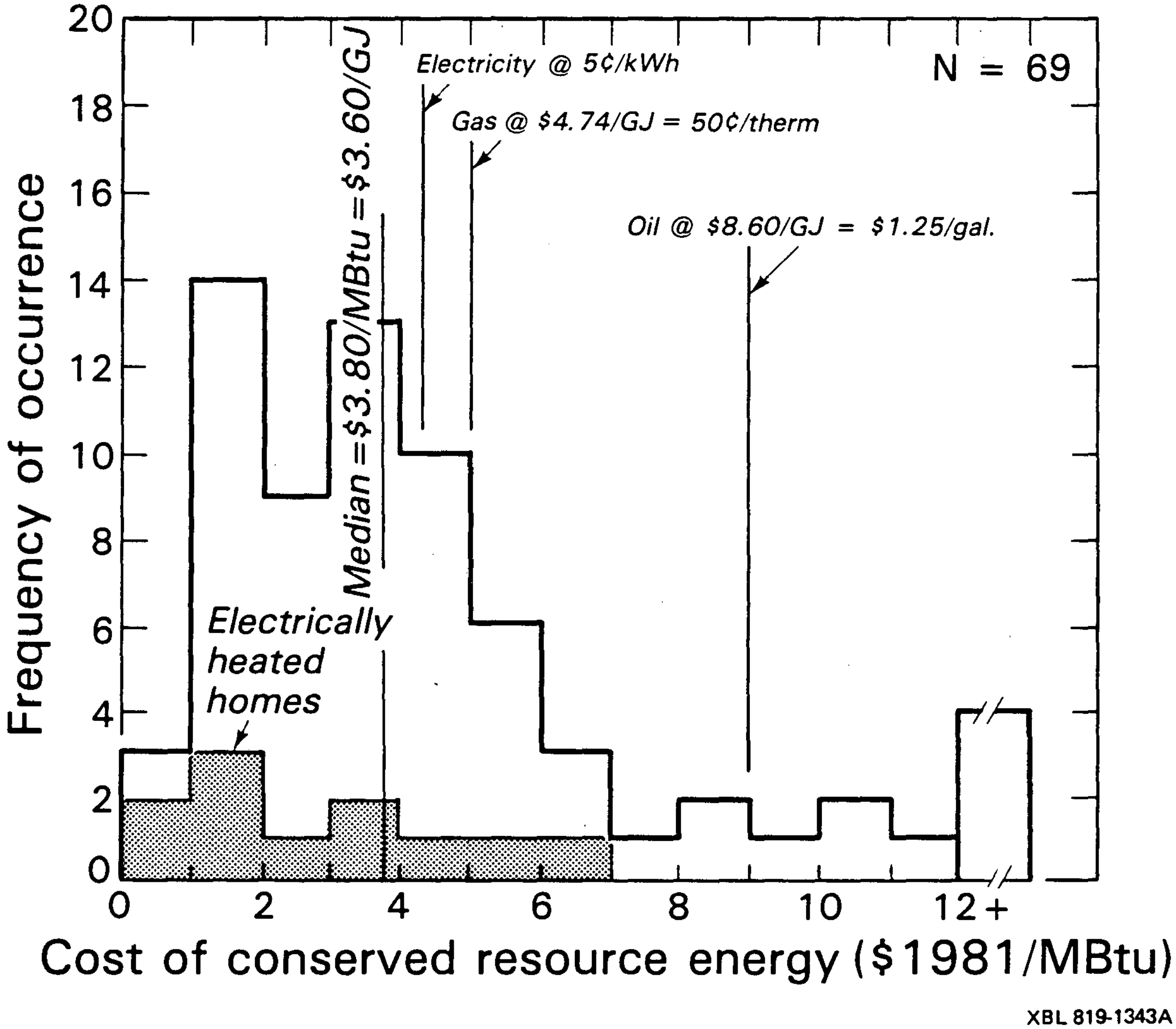


Fig. 7. Histogram of the distribution of cost of conserved energy (CCE) for the sample. CCE values for electrically heated homes are shown in the shaded area with a median of 3.1¢/kWh. Overall, the 69 entries obtained a median cost of conserved energy of $3.60/GJ [$3.80/MBtu].

January 28, 1983

APPENDIX A: Summary Data Table

The following table represents the data collected and calculated for this study. The explanation of the table headings is as follows:

Column A: Label for each data source

First letter signifies the fuel type used for heating.

"G" = natural gas

"M" = mixed fuel--heating fuel differed from house to house within a study sample

"O" = fuel oil

"E" = electricity

If the letter "A" immediately follows the fuel type symbol, then the home is an Apartment or multifamily dwelling. If no second letter follows the fuel type symbol, then the home is a single-family dwelling.

The number after initial letter(s) is simply a counting index to label each different retrofit data sample.

At a particular site if there is more than one sample group for which consumption data was accumulated by the evaluators, then we use a decimal point after the first number (counting index) followed by 1, 2, 3, ... to denote the additional groups.

The letter "A" or "B" at the end of the entry signifies an "active" or a "blind" control group.

Example: "G7.3A" signifies a gas-heated single-family home which is at the 7th site and which is the third group at that site. Also it's an active control group.

Column B: Sponsor Category

"R" means a research study.

"U" means a utility-sponsored program.

"G" means a government program.

"P" means a private firm specializing in building energy services.

Column C: Number of Homes

The number of homes for which actual consumption data are analyzed.

Column D: Location

Column E: Sponsor

Column F: Heating Degree-Days ($18.3^{o}C = 65^{o}F$ Base)

The 30-year average of heating degree-days for the retrofit site(s).

Column G: Year of Retrofit

The actual year of retrofit or the median year in cases where there was a large sample of homes retrofitted over several years.

Column H: Average Floor Area (sq. meters)

Column I: Types of Retrofits

"I" = insulation of ceilings, floors, basement, or walls

"W" = double or triple glazing of windows

"D" = storm doors or insulating doors

"C" = caulking and weatherstripping

"T" = clock thermostats

"E" = energy management control systems

"H" = replacement or adjustment of HVAC equipment

"O" = operation & maintenance actions which affect manner in which the HVAC equipment is run

"A" = all architectural changes to the actual structure which affects its energy consumption (such as passive solar wall)

"P" = blower door pressurization and sealing of bypass and infiltration losses

No symbol for hot water retrofits because they are indicated in Column J.

Column J: Energy Usage

"H" = space heating consumption only is included in the consumption data

"W" = space heating and domestic hot water heating are included in the consumption data

"F" = consumption includes all uses for space heating fuel; generally includes water heating, cooking, clothes drying, etc.

Column K1: Energy consumption in GJ or kWh per year before retrofit (1.055 GJ = 1MBtu)

Column K2: Energy consumption in GJ or kWh per year after retrofit

Column K3: Annual energy savings in GJ or kWh

Column K4: Percentage savings

Column L1: Average contractor cost in year of retrofit

Column L2: Average retrofit costs in 1981 dollars (costs are normalized to 1981 dollars using the GNP Implicit Price Deflators)

Column L3: Average retrofit costs (in 1981 dollars) per sq. meter (calculated only if average floor area of the sample group is available)

Column M1: Cost of conserved energy (in 1981 dollars) per GJ or in cents/kWh using a Capital Recovery Rate (CRR) of 8.38%, corresponding to a 15-year amortization period at 3% real discount rate.

Column M2: CCE in '81\$/GJ or in '81¢/kWh using a CRR of 11.0% (7% real discount for 15 years)

Column M3: CCE in '81\$/GJ or in '81¢/kWh using a CRR of 13.2% (10% real discount for 15 years)

Column N: Simple payback time (years)

Type "a" $$SPT^{(a)} = \frac{\text{Cost of Investment (Original \$)}}{\text{(Energy Savings/Yr) (Local price of Energy in Orig. \$)}}$$

Type "b" $$SPT^{(b)} = \frac{\text{Cost of Investment (1981 \$)}}{\text{(Energy Savings/Yr) (Local price of Energy in 1981\$)}}$$

Type "c" $$SPT^{(c)} = \frac{\text{Cost of Investment (Original \$)}}{\text{(Energy Savings/Yr) (National Average Cost of Energy for that fuel in Orig. \$ for Jan. of 1st post-retro Winter)}}$$

Type "a" is the most common calculation for SPT in our data, The superscript "(a)" has been suppressed in the Table so that no superscript means a type "a" SPT.

Column O1: Heating Fuel Intensity in MJ/m^2 before retrofit (for electric heating, we convert to resource energy using 12 MJ per kWh sold) [$MJ/m^2 \times 0.088 = MBtu/1000\ ft^2$]

Column O2: Heating Fuel Intensity in MJ/m^2 after retrofit (again for electric heating, we convert to resource energy using 12 MJ per kWh sold)

Column P1: Fuel Integrity of the dwelling in $KJ/m^2\text{-}DD_C$ before retrofit (for electric heating, we multiply by 1.5 to normalize for the different fuel efficiency of an electric heating system compared to a gas or oil system i.e., used a ratio of 5.4 MJ per kWh). [$KJ/m^2\text{-}DD_C \times 0.049 = Btu/ft^2\text{-}DD_F$]

Column P2: Fuel Integrity of the dwelling in $KJ/m^2\text{-}DD_C$ after retrofit (again for electric heating, we multiply by 1.5 to eliminate the different fuel efficiency of an electric heating system compared to a gas or oil system)

NOTE: We caution our readers that the fuel integrity values listed in Columns P1 and P2 give only approximate relative values of the performances of a building shell and heating system. Our lack of knowledge about interior thermostat settings, other occupant management variables and other sources of "free heat" (appliances, solar gains etc.) is built into the fuel integrity values. In addition, dividing the fuel usage by the number of heating degree-days to the base 18.3^{o}C is an acceptable but not a precise method of weather-normalizing homes in different locations.

Column Q: Confidence level for the data

"A" = high confidence in the data. Generally this designation requires either submetered data or regression analysis that estimates the balance point temperature and baseload usage and adjusts for weather, using HDD's calculated to the reference balance point temperature. Detailed weather information (daily or monthly HDD's) and accurate cost data are collected. A control group is usually part of the experimental design.

"B" = medium high confidence. Baseload adjustment consists of subtracting off the summer months' values of fuel usage. The weather adjustment is usually a simple scaling based on monthly HDD's (base 18.3^{o}C).

"C" = average confidence. A simplified baseload correction is made and the weather correction consists of scaling by annual HDD's (base 18.3^{o}C). Some uncertainty exists in retrofit cost data.

"D" = low confidence. Sufficient flaws exist in the data to cast doubt on the results. No baseload correction or weather adjustment is made. Consumption and cost data are not carefully collected.

"F" = no confidence. Very crude data with much missing information. Major flaws exist in the data.

(No "D" or "F"-level data are included in this study).

"I" = incomplete. Certain key data are missing but may be available in the future so that the analysis can be completed.

Column R: Comments

Additional descriptive comments for that particular entry.

Appendix A. Summary data table.

A	B	C	D	E	F	G	H	I	J	K1	K2	K3	K4
LABEL	SPONS CAT.	NUMBER OF HOMES	LOCATION	SPONSOR	HDD (C)	YR OF RETRO FIT	FLOOR AREA (SQM)	RETROFIT MEASURES	ENERGY USAGE	ENERGY BEFORE (GJ/ YR)	CONSUMP AFTER (GJ/ YR)	ENERGY (GJ/ YR)	SAVINGS (PER CENT)
G1	R	1	BOWMAN HOUSE,MD	NBS	2561	75	191	I,W,C	H	132.5	55.0	77.5	59
G2	R	1	TWIN RIVERS,NJ	PRINCETON	2728	77	139	I,W,C,P	H	85.5	20.3	65.2	76
G3	R	1	HS 11,NJ	PRINCETON	2728	79	112	I,W,H,P	H	62.9	37.7	25.2	40
G4	R	1	HS 22,NJ	PRINCETON	2728	79	145	I,D,H,P	H	120.7	88.7	32.0	26
G5.1	R/U	6	MRE/FREEHOLD,NJ	PRINCETON/NJNG	2707	80	232	I,T,P	F	188.6	142.5	46.1	24
G5.2	R/U	12	MRE/FREEHOLD,NJ	PRINCETON/NJNG	2707	80	232	T,P	F	181.4	150.8	30.6	17
G5.3B	R/U	6	MRE/FREEHOLD,NJ	PRINCETON/NJNG	2707		232		F	194.1	184.5	9.6	5
G5.4B	R/U	140000	MRE/NJNG	PRINCETON/NJNG	2707				F				3
G6.1	R/U	6	MRE/TOMS RIVER,NJ	PRINCETON/NJNG	2707	80	84	I,T,P	F	92.0	74.3	17.7	19
G6.2	R/U	12	MRE/TOMS RIVER,NJ	PRINCETON/NJNG	2707	80	84	T,P	F	104.7	97.5	7.2	7
G6.3B	R/U	6	MRE/TOMS RIVER,NJ	PRINCETON/NJNG	2707		84		F	103.4	103.4	0.0	0
G6.4B	R/U	140000	MRE/NJNG	PRINCETON/NJNG	2707				F				4
G7.1	R/U	6	MRE/OAK VALLEY,NJ	PRINCETON/SJG	2707	80	130	I,T,P,W	F	122.7	93.8	28.9	24
G7.2	R/U	9	MRE/OAK VALLEY,NJ	PRINCETON/SJG	2707	80	130	T,P	F	127.5	99.2	28.4	22
G7.3A	R/U	6	MRE/OAK VALLEY,NJ	PRINCETON/SJG	2707		130		F	135.7	121.3	14.3	11
G7.4B	R/U	75000	MRE/SJG	PRINCETON/SJG	2707				F				11
G8.1	R/U	5	MRE/WHITMAN SQ,NJ	PRINCETON/SJG	2707	80	186	I,T,P	F	155.3	117.9	37.3	24
G8.2	R/U	9	MRE/WHITMAN SQ,NJ	PRINCETON/SJG	2707	80	186	T,P	F	142.2	115.1	27.1	19
G8.3A	R/U	4	MRE/WHITMAN SQ,NJ	PRINCETON/SJG	2707		186		F	141.2	118.6	22.6	16
G8.4B	R/U	75000	MRE/SJG	PRINCETON/SJG	2707				F				12
G24.1	R/U	6	MRE/EDISON,NJ	PRINCETON/ELIZ.GAS	2707	80	167	I,T,P	F	172.4	131.7	40.7	24
G24.2	R/U	5	MRE/EDISON,NJ	PRINCETON/ELIZ.GAS	2707	80	167	T,P	F	172.8	147.4	25.4	15
G24.3A	R/U	6	MRE/EDISON,NJ	PRINCETON/ELIZ.GAS	2707		167		F	175.4	163.2	12.2	7
G24.4B	R/U	75000	MRE/ELIZ. GAS	PRINCETON/ELIZ.GAS	2707				F				10
G25.1	R/U	6	MRE/WOOD RIDGE,NJ	PRINCETON/PSEG	2707	80	130	I,P	F	186.3	159.1	27.2	15
G25.2	R/U	6	MRE/WOOD RIDGE,NJ	PRINCETON/PSEG	2707	80	130	P	F	167.7	145.3	22.5	13
G25.3A	R/U	6	MRE/WOOD RIDGE,NJ	PRINCETON/PSEG	2707		130		F	155.9	138.4	17.5	11
G25.4B	R/U	550000	MRE/PSEG,NJ	PRINCETON/PSEG	2707				F				11
G26.1	R/U	5	MRE/NEW ROCHELLE,NY	PRINCETON/CONED	2707	80	130	I,T,P,H	F	163.9	130.9	33.0	20
G26.2	R/U	5	MRE/NEW ROCHELLE,NY	PRINCETON/CONED	2707	80	130	T,P,H	F	169.2	143.6	25.6	15
G26.3A	R/U	6	MRE/NEW ROCHELLE,NY	PRINCETON/CONED	2707		130		F	167.6	145.9	21.7	13
G9.1	R	5	SASKATCHEWAN,CANADA	EN.CONS INFO C./NRC	6077	80	200	I,C,P	H	186.8	130.6	56.2	30
G9.2	R	5	SASKATCHEWAN,CANADA	EN.CONS INFO C./NRC	6077	80	163	C,P	H	172.5	156.8	15.7	9
G9.3	R	10	SASKATCHEWAN,CANADA	EN.CONS INFO C./NRC	6077	80		I,W,D,C	H	134.2	117.4	16.8	13
G10.1	R	1	BUTTE,MT	NCAT	5372	79	214	I	H	284.0	256.4	27.6	10
G10.2	R	1	BUTTE,MT	NCAT	5372	80	214	I,C,A	H	256.4	175.0	81.3	32
G11	U	84	RAMSEY COUNTY,MINN	NSP	4533	79	177	I,C	H	165.3	152.9	12.4	8
G12.1	U	33	BAKERSFIELD,CA	PGE	1214	79		I	H	87.6	71.8	15.7	18
G12.2	U	16	FRESNO,CA	PGE	1472	79		I	H	64.9	44.3	20.6	32
G13	U	33000	COLORADO	PUB SERV CO	3342	77		I	H	125.8	105.1	20.7	16
G14.1	G	8	OAKLAND,CA	CSA/NBS	1616	79	121	I,C	H	80.3	78.0	2.3	3
G14.2A	G	4	OAKLAND,CA	CSA/NBS	1616				H	123.3	135.5	-12.1	-10
G15	G	18	ST LOUIS,MO	CSA/NBS	2639	79	126	I,W,C	H	184.3	166.0	18.4	10
G16	G	10	CHICAGO,ILL	CSA/NBS	3404	79	136	I,W,C,H	H	279.4	163.6	115.7	41
G17.1	G	16	COLORADO SPRINGS	CSA/NBS	3596	79	93	I,W,C,H	H	139.3	75.5	63.7	46
G17.2A	G	4	COLORADO SPRINGS	CSA/NBS	3596				H	173.9	173.7	0.2	0
G18.1	G	17	ST PAUL,MINN	CSA/NBS	4533	79	132	I,W,C	H	190.8	149.4	41.5	22
G18.2A	G	5	ST PAUL,MINN	CSA/NBS	4533				H	301.8	277.1	24.7	8
G19	G	30	LUZERNE CTY,PA	DOE	3487	79		I,W,C	H	166.6	141.6	25.0	15
G20	G	89	LOUISIANA	DOE	1000	80			H	51.0	36.0	15.0	29

Appendix A. Summary data table, continued.

A	B	C	D	E	F	G	H	I	J	K1	K2	K3	K4
LABEL	SPONS CAT.	NUMBER OF HOMES	LOCATION	SPONSOR	HDD (C)	YR OF RETRO FIT	FLOOR AREA (SQM)	RETROFIT MEASURES	ENERGY USAGE	ENERGY BEFORE (GJ/ YR)	CONSUMP AFTER (GJ/ YR)	ENERGY (GJ/ YR)	SAVINGS (PER CENT)
G21.1	G	21	KANSAS CITY,MO	DOE	2867	77		I,C	H	142.4	121.3	21.1	15
G21.2	G	45	KANSAS CITY,MO	DOE	2867	77		I,C	H	206.8	160.4	46.4	22
G21.3	G	44	KANSAS CITY,MO	DOE	2907	78		I,C	H	201.5	146.6	54.9	27
G22	G	138	KENTUCKY	DOE	2627	79		I,W,D,C	H	125.0	108.5	16.6	13
G23	G	30	INDIANA	DOE	3098	78	102	I,C,H	H	192.1	143.2	49.0	25
O1	R	1	HS 21,NJ	PRINCETON	2728	79	185	I,W,H,P	H	139.3	65.9	73.3	53
OA2.1	G/P	159	PAGE APTS, NJ	HUD/TRENTON	2728	81	77	H,E	W	101.5	51.2	50.3	50
OA2.2B	R	1500	APTS,NJ	HUD/TRENTON	2728				W	123.1	103.7	19.4	16
OA3	P	521	MF COMPLEX,WASH DC	SCALLOP THERMAL MAN.	2339	78		H,E,O	W	122.7	114.4	8.3	7
OA4	P	752	MF COMPLEX,MD	SCALLOP THERMAL MAN.	2339	78		H,E,O	W	89.6	87.7	1.9	2
OA5	P	60	COOP BLDG,NYC	SCALLOP THERMAL MAN.	2693	78		H,E,O	W	176.5	160.5	16.0	9
O6	G	13	VERMONT	DOE	4376	80		I,W,D	H	151.4	105.5	45.9	30
M1.1	G	13	CHARLESTON,SC	CSA/NBS	1192	79	103	I,C	H	65.9	43.7	22.3	34
M1.2A	G	5	CHARLESTON,SC	CSA/NBS	1192				H	38.3	32.4	5.9	15
M2	G	8	ATLANTA,GA	CSA/NBS	1719	79	98	I,W,C	H	114.0	99.3	14.8	13
M3	G	4	WASH,DC	CSA/NBS	2339	79	85	I,W,C,H	H	137.7	72.9	64.8	47
M4.1	G	9	TACOMA,WA	CSA/NBS	2881	79	91	I,W,C	H	178.1	105.3	72.8	41
M4.2A	G	5	TACOMA,WA	CSA/NBS	2881				H	62.8	52.9	9.9	16
M5.1	G	13	EASTON,PA	CSA/NBS	3237	79	124	I,C,H	H	128.4	98.2	30.2	24
M5.2A	G	3	EASTON,PA	CSA/NBS	3237				H	46.4	42.1	4.4	9
M6.1	G	14	PORTLAND,ME	CSA/NBS	4166	79	94	I,W,C,H	H	197.6	111.2	86.4	44
M6.2A	G	4	PORTLAND,ME	CSA/NBS	4166				H	245.3	215.0	30.3	12
M7.1	G	12	FARGO,ND	CSA/NBS	5151	79	73	I,W,C,H	H	115.5	69.4	46.1	40
M7.2A	G	5	FARGO,ND	CSA/NBS	5151				H	153.1	138.5	14.6	10
M8.1	G	142	CSA/NBS	COMPOSITE		79	109		H	154.8	107.5	47.3	31
M8.1A	G	41	CSA/NBS	COMPOSITE					H	153.2	146.3	6.9	4
M9	G	65	NW WISCONSIN	CSA	4660	76	120	I,W,D,C	H	150.9	122.3	28.6	19
M10.1	G	59	MINNESOTA	DOE	4617	78	75	I,W,C	H	117.0	105.1	11.9	10
M10.2B	G	37	MINNESOTA	DOE	4617		123		H	135.6	138.9	-3.4	- 2
M10.3	G	19	MINNESOTA	DOE	4617	78	72	I,W,C	H	109.3	102.0	7.3	7
M11	G	13	WISCONSIN	DOE	4900	79			H	147.0	122.7	24.3	17
M12	G	86	ALLEGAN CTY,MI	DOE	3778	80			H	164.6	118.2	46.4	28
										(KWH)		(KWH)	
E1.1	U	69	TENNESSEE	TVA	2464	76	94	I,C	H	11270.0	5148.0	6122.0	54
E1.2	U	105	TENNESSEE	TVA	2456	76		I	H	12383.0	8271.0	4112.0	33
E2	U	546	TENNESSEE	TVA	2228	78		I	H	10148.0	7937.0	2211.0	22
E3.1	R/P	29	DENVER,COL	JOHNS MANVILLE	3342	78	149	P	H	17615.0	14779.0	2836.0	16
E3.2A	R/P	30	DENVER,COL	JOHNS MANVILLE	3342				H	20606.0	17715.0	2891.0	14
E3.3B	R/P	30	DENVER,COL	JOHNS MANVILLE	3342				H	23886.0	21034.0	2852.0	12
E4	U	1896	OREGON	PAC PWR LIGHT	2667	79		I,W,D,C	H	21305.0	17044.0	4261.0	20
E5.1	U	133	SEATTLE,WA	SEATTLE CITY LIGHT	2881	79		I	H	17107.0	12934.0	4173.0	24
E5.2B	U	551	SEATTLE,WA	SEATTLE CITY LIGHT	2881				H	16843.0	14634.0	2209.0	13
E6	U	8802	WASHINGTON	PUGET POWER	3056	79		I,W	H	20000.0	13070.0	6930.0	35
E7	U	161	OREGON	PORTLAND GEN ELEC	2662	78		I,W,D,C	H	13000.0	8879.0	4121.0	32
E8.1	R/U	5	MIDWAY,WA	BPA/LBL	2644	80	117	P	H	19984.0	18138.0	1846.0	9
E8.2	R/U	5	MIDWAY,WA	BPA/LBL	2644	79	116	I,C	H	19803.0	16568.0	3235.0	16
E8.3	R/U	4	MIDWAY,WA	BPA/LBL	2644	79	115	I,C,D,W	H	19649.0	11445.0	8204.0	42

Appendix A. Summary data table, continued.

A	L1	L2	M1	M2	M3	N	O1	O2	P1	P2	Q	R
LABEL	COST OF RETRO FIT (ORIG$)	COST OF RETRO FIT (81$)	COST ENERGY (CRR =8.4)	OF (81$/ (CRR =11.0)	CONS. GJ) (CRR =13.2)	SIMPLE PAYBACK (YEARS)	HEATING FUEL INTENS. BEFORE (GJ/ 100SQM)	HEATING FUEL INTENS. AFTER (GJ/ 100SQM)	FUEL INTEGR BEFORE (KJ/ SQMDD)	FUEL INTEGR AFTER (KJ/ SQMDD)	CONFI- DENCE LEVEL	COMMENTS
G1	2840	4202	4.54	5.95	7.15	16.1	69.4	28.8	271	112	A	FIRST EXTENSIVE STUDY
G2	3000	4036	5.19	6.80	8.17	16.2	61.3	14.5	225	53	A	TOWNHOUSE
G3	700	814	2.70	3.54	4.26	7.9	56.4	33.8	207	124	A	ELIMINATE BYPASS LOSSES,ETC.
G4	1000	1162	3.05	3.99	4.80	8.9	83.3	61.2	305	224	A	ELIMINATE BYPASS LOSSES,ETC.
G5.1	2562	2750	5.00	6.55	7.87	13.0	50.9	34.8	188	129	A	H. D. AND CONTRACT RETR.
G5.2	325	349	0.96	1.25	1.51	2.5	51.5	44.8	190	166	A	H. D. ONLY
G5.3B							60.3	59.7	223	221	A	BLIND CONTROL GROUP
G5.4B											A	UTILITY AGGREGATE
G6.1	1272	1365	6.46	8.46	10.17	16.8	75.8	57.5	280	212	A	H. D. AND CONT. RET.
G6.2	325	349	4.08	5.34	6.42	10.6	83.0	78.0	307	288	A	H. D. ONLY
G6.3B							87.4	87.4	323	323	A	BLIND CONTROL GROUP
G6.4B											A	UTILITY AGGREGATE
G7.1	911	978	2.84	3.71	4.47	6.2	55.3	38.2	204	141	A	H. D. AND CONTRACT RETR.
G7.2	325	349	1.03	1.35	1.62	2.2	53.7	40.4	198	149	A	H. D. ONLY
G7.3A							58.6	48.1	216	178	A	ACTIVE CONTROL GROUP
G7.4B											A	UTILITY AGGREGATE
G8.1	664	713	1.60	2.10	2.52	3.5	70.8	52.0	261	192	A	H. D. AND CONTR. RETR.
G8.2	325	349	1.08	1.41	1.70	2.3	57.5	45.9	212	170	A	H. D. ONLY
G8.3A							58.7	45.4	217	167	A	ACTIVE CONTROL GROUP
G8.4B											A	UTILITY AGGREGATE
G24.1	1370	1471	3.03	3.97	4.77	7.1	68.6	46.5	253	172	A	H. D. AND CONTRACT RETR.
G24.2	325	349	1.15	1.51	1.81	2.7	66.4	52.6	245	194	A	H. D. ONLY
G24.3A							72.5	57.5	268	212	A	ACTIVE CONTROL GROUP
G24.4B											A	UTILITY AGGREGATE
G25.1	961	1032	3.18	4.16	5.00	7.4	104.6	75.8	386	280	A	H. D. AND CONTRACT RETR.
G25.2	325	349	1.30	1.70	2.05	3.1	93.0	71.9	343	266	A	H. D. ONLY
G25.3A							89.1	70.2	329	259	A	ACTIVE CONTROL GROUP
G25.4B											A	UTILITY AGGREGATE
G26.1	1008	1082	2.75	3.60	4.33	6.4	80.8	63.1	298	233	A	H. D. AND CONTRACT RETR.
G26.2	325	349	1.14	1.49	1.80	2.7	71.4	60.8	264	225	A	H. D. ONLY
G26.3A							90.8	77.5	335	286	A	ACTIVE CONTROL GROUP
G9.1	1976	2027	3.02	3.96	4.76	12.3B	93.2	65.2	153	107	B	SEALED AND INSULATED
G9.2	514	527	2.81	3.68	4.43	11.5B	106.0	96.3	174	158	B	SEALED ONLY
G9.3	1442	1479	7.39	9.68	11.64	30.2B					C	INSULATED
G10.1	500	570	1.73	2.27	2.72	5.4B	132.9	120.0	247	223	B	PHASE I
G10.2	13100	13737	14.15	18.54	22.29	44.5B	120.0	81.9	223	152	B	PHASE II, INCLUDES PASSIVE WALL
G11	290	325	2.18	2.86	3.44	8.4	93.7	86.6	206	191	B	LOW-INCOME WEATHERIZATION
G12.1	427	496	2.65	3.47	4.17	5.7					B	ATTIC INSUL PROG IN SAN JOAQUIN VALLEY
G12.2	417	485	1.97	2.58	3.10	4.3					B	ATTIC INSUL PROG IN SAN JOAQUIN VALLEY
G13	272	360	1.46	1.91	2.30	4.4B					B	LOW INT LOANS FOR ATTIC INSUL
G14.1	274	312	11.49	15.06	18.10	18.9	66.5	64.6	411	400	A	DEMO PGM. LOW-INCOME WEATHERIZATION
G14.2A											A	ACTIVE CONTROL GRP.
G15	1781	2031	9.27	12.15	14.61	43.6	146.4	131.8	555	499	A	DEMO PGM. LOW-INCOME WEATHERIZATION
G16	2347	2677	1.94	2.54	3.05	7.3	205.4	120.3	603	353	A	DEMO PGM. LOW-INCOME WEATHERIZATION
G17.1	1765	2013	2.65	3.47	4.17	12.0	150.2	81.5	418	226	A	DEMO PGM. LOW-INCOME WEATHERIZATION
G17.2A											A	ACTIVE CONTROL GROUP
G18.1	1761	2008	4.06	5.32	6.39	15.7	144.6	113.2	319	250	A	DEMO PGM. LOW-INCOME WEATHERIZATION
G18.2A											A	ACTIVE CONTROL GROUP

Appendix A. Summary data table, continued.

A	L1	L2	M1	M2	M3	N	O1	O2	P1	P2	Q	R
LABEL	COST OF RETRO FIT (ORIG$)	COST OF RETRO FIT (81$)	COST ENERGY (CRR =8.4)	OF (81$/ (CRR =11.0)	CONS. GJ) (CRR =13.2)	SIMPLE PAYBACK (YEARS)	HEATING FUEL INTENS. BEFORE (GJ/ 100SQM)	HEATING FUEL INTENS. AFTER (GJ/ 100SQM)	FUEL INTEGR BEFORE (KJ/ SQMDD)	FUEL INTEGR AFTER (KJ/ SQMDD)	CONFI-DENCE LEVEL	COMMENTS
G19	789	900	3.02	3.95	4.75	9.2					C	LOW-INCOME WEATHERIZATION
G20	1044	1071	5.99	7.85	9.44	17.9					C	LOW-INCOME WEATHERIZATION
G21.1	407	539	2.14	2.80	3.37	13.0					C	LOW-INCOME WEATHERIZATION
G21.2	525	675	1.22	1.60	1.92	7.6					C	LOW-INCOME WEATHERIZATION
G21.3	1494	1814	2.77	3.63	4.36	15.5					C	LOW-INCOME WEATHERIZATION
G22	254	290	1.47	1.92	2.31	4.6C					C	LOW-INCOME WEATHERIZATION
G23	1375	1700	2.91	3.81	4.59	14.1C	187.7	139.8	605	451	B	LOW-INCOME WEATHERIZATION
O1	1200	1395	1.59	2.09	2.51	3.1	75.3	35.7	276	131	A	ELIM. BYPASS LOSSES
OA2.1	252	244	0.41	0.53	0.64	0.6	131.6	66.4	482	243	B	MULTI-FAMILY APT. RETROFIT
OA2.2B											B	BLIND CONTROL GROUP
OA3			3.27	3.37	3.49	9.0C					B	THERMAL SERVICES CONTRACT
OA4			8.53	8.87	9.09	23.6C					B	THERMAL SERVICES CONTRACT
OA5											I	THERMAL SERVICES CONTRACT
O6	1506	1579	2.88	3.78	4.54	4.1					C	LOW-INCOME WEATHERIZATION
M1.1	977	1114	4.19	5.50	6.61	6.6	63.9	42.3	536	355	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M1.2A											A	ACTIVE CONTROL GROUP
M2	1211	1381	7.84	10.27	12.34	18.9	116.4	101.3	677	589	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M3	2924	3335	4.31	5.65	6.80	6.3	162.0	85.8	692	366	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M4.1	1807	2061	2.37	3.11	3.74	8.4	196.0	115.9	680	402	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M4.2A											A	ACTIVE CONTROL GROUP
M5.1	905	1032	2.87	3.76	4.52	6.1	103.6	79.3	320	245	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M5.2A											A	ACTIVE CONTROL GROUP
M6.1	2215	2526	2.45	3.21	3.86	3.8	211.0	118.7	507	285	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M6.2A											A	ACTIVE CONTROL GROUP
M7.1	1626	1854	3.37	4.42	5.31	5.7	158.2	95.1	307	184	A	DEMO PGM. LOW-INCOME WEATHERIZATION
M7.2A											A	ACTIVE CONTROL GROUP
M8.1	1610	1836	3.26	4.27	5.13	8.2	142.6	99.1			A	DEMO PGM. LOW-INCOME WEATHERIZATION
M8.1A											A	ACTIVE CONTROL GROUP COMPOSITE
M9	219	307	0.90	1.18	1.42	2.4	125.7	101.9	270	219	C	LOW-INCOME WEATHERIZATION
M10.1	906	1120	7.88	10.32	12.41	25.1C	156.3	140.3	338	304	C	LOW-INCOME WEATHERIZATION
M10.2B							110.1	112.9	239	244	C	BLIND CONTROL GROUP
M10.3	849	1050	12.09	15.84	19.04	36.0	152.0	141.9	329	307	C	2 POST-RETRO YEARS SUBGROUP
M11	1088	1241	4.29	5.61	6.75	11.1					C	LOW-INCOME WEATHERIZATION
M12	1050	1101	1.99	2.60	3.13	3.9					C	LOW-INCOME WEATHERIZATION
				CENTS/KWH								
E1.1	440	610	0.83	1.09	1.31	3.5	145.3	66.4	263	120	A	DEMO PROGRAM BY PRIVATE CONTRAC.
E1.2	154	213	0.43	0.57	0.68	1.9					B	DEMO PROGRAM BY TVA PERSONNEL
E2	310	383	1.45	1.90	2.29	5.1					A	EARLY PART OF HOME INSUL. PROG
E3.1	1050	1245	3.68	4.82	5.80	7.7B	143.8	120.6	192	161	A	STUDY OF AIR LEAKAGE
E3.2A											A	ACTIVE CONTROL GROUP
E3.3B											A	BLIND CONTROL GROUP
E4	1335	1523	2.99	3.92	4.72	13.6					C	ZERO INTEREST WEATH. PROGRAM
E5.1	399	455	0.91	1.20	1.44	5.1					C	EARLY PART OF WEATH. PROGRAM
E5.2B											C	BLIND CONTROL GROUP
E6	1110	1266	1.53	2.01	2.41	6.8B					C	ZERO INTEREST WEATH. PROGRAM
E7	1357	1609	3.27	4.29	5.15	9.4					C	EARLY PART OF WEATH. PROGRAM
E8.1	525	525	2.38	3.12	3.75	11.4	207.1	188.0	349	317	A	EXTENDED INFILTRATION REDN.
E8.2	1860	2041	5.29	6.93	8.33	23.0	206.4	172.7	348	291	A	ATTIC AND CRAWLSPACE INS.
E8.3	4023	4415	4.51	5.91	7.10	19.6	207.1	120.6	349	203	A	INS. PLUS STORM DOOR,WINDOW

APPENDIX B: Price Equivalency of Resource Energy Units

An advantage of using resource electricity units is that the costs per gigajoule for fuel and electricity end up roughly equivalent. This point is illustrated in the table below, based on data extracted from the Monthly Energy Review (MER, Oct. 1982).

Appendix B. Residential energy prices in June 1982 and equivalent cost in resource energy.

Fuel	Thermal Conversion	National Avg. Residential Price	Cost per unit of Thermal Energy ($/GJ)
Natural Gas	1.08 MJ/cf	$5.61/kcf	$5.19/GJ
Heating Oil	6.15 GJ/barrel	$1.16/gal	$7.93/GJ
Gas and Oil, consumption weighted*	--	--	$6.03/GJ
Electricity "Site"	3.6 MJ/kWh	$0.0708/kWh	$19.67/GJ
"Resource"	12.1 MJ/kWh	$0.0708/kWh	$5.85/GJ

*In 1980, the residential buildings sector used 5.3 quads of gas (69%) and 2.4 quads of oil (31%). Using these fractions to weight the gas and oil prices, we obtain a weighted average price of $6.03/GJ, relatively close to the resource electricity price of $5.85/GJ.

In Appendix A, we show energy consumption data from electrically-heated homes in kilowatt-hours. These values are then converted to resource electricity units in Figures 1,4, and 6, to provide a comparable basis for evaluation with gas- or oil-heated residences.

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