Lawrence Berkeley National Laboratory
Recent Work

Title

MEASURED RESULTS OF ENERGY CONSERVATION RETROFITS IN RESIDENTIAL BUILDINGS

Permalink

https://escholarship.org/uc/item/70f4h1fs

Author

Goldman, C.A.

Publication Date

1985-07-01

eScholarship.org Powered by the California Digital Library
University of California

UC-95d
LBL-20950
c.1

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Presented at the 1986 ASHRAE Winter Meeting
San Francisco, CA, January 19-22, 1986

RECEIVED
LAWRENCE
BERKELEY LABORATORY
APR 7 1986
LIBRARY AND
DOCUMENTS SECTION

MEASURED RESULTS OF ENERGY CONSERVATION RETROFITS IN RESIDENTIAL BUILDINGS

C.A. Goldman

July 1985

For Reference

Not to be taken from this room

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-20950 c.1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Presented at 1986 ASHRAE Winter
Meeting - San Francisco, CA, January 19-22, 1986

LBL-20950
EEB-BED-85-09

MEASURED RESULTS OF ENERGY CONSERVATION RETROFITS IN RESIDENTIAL BUILDINGS

Charles A. Goldman

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 1985

* The work described in this report was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ABSTRACT

This study summarizes measured data on energy savings from conservation retrofits in existing residential buildings. Retrofits to the building shell, principally insulation of exterior surfaces, window treatments, and infiltration-reduction measures, are the most popular, although data on various heating system retrofits are now available. The average retrofit investment per unit in multifamily buildings is approximately $700, far lower than the average of $1350 spent in single-family residences. Savings achieved are typically 20% to 30% of pre-retrofit space heating energy use, although large variations are observed both in energy savings and in costs per unit of energy saved. Particularly cost-effective retrofit strategies are identified based on measured energy use data. Predicted versus actual savings are also compared for groups of homes in 24 retrofit projects.

KEYWORDS

Energy Conservation, Space Heating, Residential Retrofits, Monitoring, Economics

INTRODUCTION

A recent Office of Technology Assessment (OTA 1982) report concluded that "despite considerable theoretical analysis and thousands of audits, there is still very little documented information on the results of actual retrofits on different types of buildings." The OTA report stresses that improved data on the results of individual retrofits, retrofit packages, and actual savings compared to predicted could help alleviate building owners' concerns regarding retrofit expense and outcome.

The Buildings Energy Data Group at the Lawrence Berkeley Laboratory addresses the lack of monitored building performance data by compiling and analyzing *measured* data that document the energy savings and cost-effectiveness of conservation measures and practices.* This study focuses on retrofitted residential buildings. Results from approximately 115 retrofit projects are presented, nearly twice as many as in the previous compilation (Wall et al 1983).

Analysis of a large data base (totaling 60,000 households) provides a fairly broad picture of retrofit performance under varying conditions, although this compilation is not a representative survey of the fraction of the housing stock that has been retrofitted in recent years. In this study, cost-effective retrofit strategies are identified based on metered energy consumption data. Factors that account for variation in energy savings among households installing similar measures are also examined. Finally, actual measured results are compared to predicted energy savings.

DATA SOURCES AND RETROFIT MEASURES

Information on retrofit projects was obtained from research organizations, utilities and government agencies that sponsor conservation programs, and firms that provide building energy services. The data collected typically included metered energy consumption, installed retrofit measures and their cost, the price of the space heating fuel the winter after retrofit, and, in most cases, a brief description of the physical characteristics of the buildings (e.g., conditioned floor area, building and heating system type). Data summary tables for each retrofit project can be found in Goldman (1985). Each project was placed in one of four broad categories (utility-sponsored conservation programs, low-income weatherization programs, research studies, retrofits of multifamily buildings) to permit a consistent and useful treatment of results. The sample size for each project varies widely, ranging from individual buildings to 33,000 homes.

* The Buildings Energy Use Compilation and Analysis (BECA) project includes studies of the energy performance of low-energy new homes (BECA-A), existing "retrofitted" buildings (BECA-B), energy-efficient new commercial buildings (BECA-CN), existing "retrofitted" commercial buildings (BECA-CR), and appliances and equipment (BECA-D).

C. A. Goldman, Staff Scientist, Energy Efficient Buildings Program, Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

Utility-sponsored conservation programs are mostly large-scale efforts that retrofit thousands of homes. They typically reach single-family, mostly middle-income homeowners. Utility programs usually offer low- or zero-interest loans to finance recommended conservation measures. Our sample has a distinct regional bias. Thirteen of the 19 conservation programs were sponsored by utilities located in the Pacific Northwest or California, and fourteen were directed at electrically heated homes.

The Department of Energy (DOE) Low-Income Weatherization Assistance Program, the CSA/NBS Weatherization Demonstration Research Project, and pilot retrofit projects for oil-fired heating systems funded by the Low-Income Energy Assistance Program are included in the low-income weatherization category. Data from a number of the DOE Weatherization Program evaluations are of questionable quality. Often, only annual utility bills or energy data for a fraction of the heating season are available, and cost data do not include labor. The CSA/NBS project involved extensive retrofitting of 142 homes in 12 different locations with detailed monitoring of energy consumption and cost data (Crenshaw and Clark 1982).

Research studies often test innovative retrofit measures or strategies. For example, Claridge et al. (1984) examined results from 26 Colorado homes that participated in the 50/50 Program, a DOE-conceived effort to speed implementation of a large number of low-cost energy conservation measures by making them available as a package. Several institutions have developed a procedure called "house doctoring" that uses diagnostic equipment (e.g., blower door pressurization and infrared scanner) to find and fix leaks and includes installation of appropriate low-cost measures (e.g., low-flow showerheads, replaced furnace filters, insulated water heaters). Sample size for research studies tends to be small (fewer than 25 homes) and a comparison or control group is usually employed as part of the experimental design. A few studies collected submetered end-use data in the post-retrofit period but most research projects relied exclusively on utility billing data.

Retrofit activity in multifamily buildings lags far behind retrofits of single-family homes. The U.S. multifamily buildings included in the data base are all located in the Northeast or Midwest. The buildings range in size from 5 to 1790 units; 68% of the buildings are larger than 50 units. The inhabitants are mostly renters and are often low-income. Fifty percent of the buildings are part of public housing projects. Three buildings were retrofitted by energy service companies who contract with building owners to manage building energy systems.

At present, most residential retrofits are directed towards improving energy efficiency in the two largest energy consumption end-uses: space heating and domestic water heating. This overall pattern can be observed in three of our data subgroups (28 multi-unit buildings, 418 homes that participated in research studies, and 142 low-income homes from the CSA/NBS weatherization project), although there are some striking differences in the relative frequency of "shell" versus heating and hot water system retrofits between the groups (Figure 1). For example, virtually all of the CSA/NBS low-income homes received "shell" retrofits, yet these measures were installed relatively infrequently in multifamily buildings. Only 15% of the multi-unit buildings installed attic insulation. The low implementation rate is due, in some cases, to adequate pre-retrofit insulation levels or to structural characteristics that make installation exorbitantly expensive (e.g., flat roofs, masonry walls). In contrast, measures designed to improve the performance of existing heating systems either by modification/replacement of equipment (e.g., burners), altered operations and maintenance practices, or installation of control systems were popular retrofit strategies in multifamily buildings.

"Shell" measures, storm windows, and hot water retrofits are most frequently installed in utility-sponsored and DOE Low-Income Weatherization programs. For example, attic insulation was the only measure implemented in six of 19 utility-sponsored programs and was an option in every program. Approximately 50% of the utility conservation programs financed floor insulation, storm windows and doors, and caulking and weatherstripping.

METHODOLOGY

The approach used in this study includes three principal elements: (1) normalizing energy use for weather effects, (2) analysis of the level and range of energy savings and identification of factors that are correlated with savings, and (3) calculation of the value of energy savings.

In almost all retrofit projects, the energy consumption data consists of monthly fuel or electricity bills that includes heating energy usage along with other ("baseline") uses of the same fuel. Regression techniques that use variable-base degree-days (VBDD) were employed in most research studies and the CSA/NBS weatherization project (Crenshaw and Clark 1982). Some utility program evaluations and research studies utilized heating degree-days to a fixed base (65 F, 18.3°C). The model is given as:

$$E = \alpha + \beta H_i(\tau) \qquad [1]$$

where

E is total gas or electricity use (depending on the buildings' heating fuel),

α is the nonheating use, and

H_i is the number of heating degree-days to base temperature, τ.

In this VBDD model, simple linear regressions are run using measured values of E and H_i to find the value of base temperature, τ, for which the R^2 statistic is highest, that is, the balance point temperature that best matches the actual house performance. The parameter, β, represents the incremental amount of gas or electricity required for each degree drop in temperature below the balance point temperature (Fels 1984). Weather-normalized annual consumption (NAC) for the pre- and post-retrofit periods is then calculated as follows:

$$NAC = 365\alpha + \beta H_o(\tau) \qquad [2]$$

where

H_o is the normal-year heating degree days to the best-fit base temperature, τ.

In most cases one or more adjustments were made to reported consumption data. Some studies used a different weather-adjustment procedure or reported only annual consumption data. In these cases, the varying severity of winter in different years was corrected for by scaling annual space heat energy use by the ratio of normal-to-actual year heating degree-days. We used the VBDD model to analyze energy use in retrofit projects where monthly utility bills were readily available. Annual baseload usage was derived either from the regression coefficient (α), calculated by scaling summer fuel use to a full year, or estimated from regional and utility data.

Retrofit costs were "standardized" based on the direct costs to the homeowner of contractor-installed measures. An equivalent contractor cost was estimated in cases where only materials costs were known (materials cost multiplied by 2.7-3.0). Costs at the time of retrofit were converted to constant dollars (1983$). Two economic indicators were calculated: simple payback time (SPT) and internal rate of return (IRR). IRR was calculated in real (or constant) dollars using a 7% real discount rate. Residential energy prices were assumed to escalate annually at a real rate of 4% (EIA, 1983a). Conservation investments are amortized over the measures' expected physical lifetimes. For multifamily buildings, estimated annual operations and maintenance costs are included in addition to the initial investment.

RESULTS

Cost-Effective Retrofit Strategies

In this section, particularly cost-effective retrofit strategies are highlighted and discussed with respect to overall results. We focus on retrofit strategies that had an average internal rate of return (IRR) greater than 20%. Our major findings are:

- The installation of attic insulation, particularly in homes with little or no insulation, resulted in cost-effective energy savings, irrespective of structural and demographic characteristics or climatic region (see Table 1).

- Conservation strategies designed to reduce domestic hot water usage, usually tank and pipe insulation, were also sound energy-efficiency investments (Table 1).
- Varying packages of "shell" retrofit measures, including attic, wall, and floor insulation, storm windows, and in some cases, weatherstripping, were successful in most single-family electric-space heated homes.
- Retrofitting existing gas- or oil-fired heating equipment appeared to be a very cost-effective complement to "shell" weatherization measures in low-income, single-family homes.
- "House-doctoring" was effective in single-family homes located in colder climates.
- Preliminary results indicate that many heating system retrofits are quite successful in multifamily buildings.

Conservation programs initiated by utilities in Tennessee (TVA) and Washington (data points E1.1 and E6.1 in Figure 2) achieved high energy savings (6100 and 8600 kWh/year) relative to cost ($700 and $1450). The TVA pilot program specifically targeted low-income, high-energy consumers; hence significant improvements in building thermal performance were obtained at low cost. Attic and floor insulation were installed in homes that participated in this program. Single-family electric-heated homes in the Washington program were eligible to receive attic, wall, or floor insulation, storm windows and doors, hot water wraps, and a clock thermostat.

The combination of heating system and shell retrofits was roughly two times more cost-effective than shell measures alone (6.4- versus 13-year payback period) for homes in the CSA/NBS Demonstration Project. Median space heat savings were 42% of pre-retrofit levels in the 73 homes (located in 7 cities) that received heating and hot water system retrofits in addition to "shell" measures (see points with x printed over circle in Figure 3), compared to median savings of 13% in the 69 homes that installed only "shell" measures.

Residents in seven groups of gas-heated New Jersey homes received "house-doctor" treatments, investing an average of $400/home. The IRR ranged between 36% and 52% in six of the seven groups (Dutt et al 1982). This retrofit strategy was also evaluated in research projects conducted by the Bonneville Power Administration and Lawrence Berkeley Laboratory. In these studies, the IRR was 1% and 13%, respectively. Researchers concluded that cost-effectiveness could be improved at these mild climate sites by focusing "house-doctoring" efforts on homes with either high infiltration rates or those that could be retrofitted with low-cost noninfiltration measures such as intermittent ignition devices and hot water wraps.

In multifamily buildings, retrofit strategies that focused on improving the efficiency of the heating system were very successful in reducing fuel costs. For example, space heat and hot water usage declined by 44% at Page Homes, a 159-unit public housing complex in Trenton, New Jersey, after the installation of a microcomputer-based boiler control system (data point O2.1 in

Figure 5). The system consists of remote temperature sensors located in selected apartments on each floor of the building and at one outdoor location. The computer controls heating system pumps and boilers based on periodic readings to maintain comfortable temperatures in each apartment (73 F, 23^{o}C). The retrofit had a one-year simple payback time. High inside temperatures (average 82 F, 28^{o}C) and the buildings' relative energy-inefficiency before retrofit (a heating factor of 23.6 Btu/ft^2 DD_F compared to the U.S. average of 15-17 Btu/ft^2 DD_F for multifamily buildings) help account for the impressive energy savings (EIA 1983b).

Annual space heat savings were between 25-58 MBtu/unit in six of eight gas-heated multifamily buildings in Chicago that are cooperatively-owned (Figure 4). Remarkable savings 119 Mbtu/unit (126 GJ/unit) were obtained in another one of these buildings (data point G31.5), a 53% reduction from pre-retrofit levels. This building was also extremely energy-inefficient before retrofit, with a heating factor of 28.7 Btu/ft^2 DD_F. Building shell measures (attic insulation and some storm windows) were installed in four of the buildings although approximately 60% of the savings were attributed to various heating system retrofits (Katrakis 1984). The heating system measures included de-rating and tuning burners in oversized heating systems (8), replacing burners (2), installation of air temperature-sensing burner controls with programmable setbacks (4), high-limit outdoor stats (7), and flue dampers (3), and balancing radiators and steam lines (8).*

Range of Energy Savings

In this section, we present the range of energy savings for *different* retrofit projects with similar investment levels and the variation in savings among households that installed identical measures and which are located in the same geographic area. We then discuss factors that are correlated with high or low energy savings as well as limitations in the data that hinder efforts to explain the observed variation.

There is substantial variation in annual space heat energy savings among single-family retrofit projects at any given investment level (Figure 2). For example, savings differ by a factor of four for an investment of $2400. It is worth noting that there seem to be few successful, cost-effective retrofits involving expenditures of more than $2500 per house.

Average space heating consumption was reduced by more than 20% in 27 of 45 single-family retrofit projects (Figure 3). Energy savings are not strongly correlated with pre-retrofit consumption levels although such a correlation is evident in results from the DOE Low-Income Weatherization program. Choice of retrofit strategy clearly influenced savings obtained by residents who participated in the CSA/NBS Project. As discussed previously, homes that received heating and

* Number in parentheses indicates buildings that received that measure.

hot water system retrofits in addition to "shell" measures performed much better than homes that installed only "shell" measures (Figure 3).

Large variations in fuel savings are also observed among households in the same geographic location that installed similar conservation measures. Weather-adjusted energy consumption declined in almost 95% of the sample, increasing in only 17 of 376 homes. The spread in energy savings among homes found between the first and third quartile (i.e., the middle 50% of the sample in Figure 5) is typically ±70% of the median savings. The large range in savings suggests that more detailed monitoring is required if we are to fully understand the relative impact of key determinants. Efforts to interpret these results are hampered by data limitations. Inside temperatures are not available for any home and in a few cases, basic information, such as conditioned floor area, was not collected (e.g., G12, G30).

However, a few preliminary conclusions can be extracted from the data. Energy savings seem to be more variable with some measures than others. For example, the coefficient of variation (CV)* in energy savings is between 0.9-1.2 in four groups of Long Island, New York, homes that retrofitted conventional burners with other options (in Figure 5, Group 5 - vent damper, Group 6 - stack heat exchanger, Group 7 - double setback thermostat, and Group 8 - thermostat and boiler temperature programmer). In contrast, savings were generally greater and more *uniform* in two similar groups that received retention head burners. The CV in energy savings is only 0.4 in homes that received the energy-efficient burners with "optimized" installation techniques (Group 2) and 0.7 in homes where typical installation procedures were used (Group 1) (Hoppe and Graves, 1982).

Energy savings for an identical measure also appear to be more variable in mild than in harsh climates. For example, utilities in California (PG&E) and Michigan evaluated conservation programs in which R-19 (RSI 3.3) attic insulation was installed in previously uninsulated homes (Williams 1980). The PG&E single-family residences were located in the San Joaquin Valley, a region with a relatively mild winter climate compared to that in Detroit, Michigan (2185 vs 6258 annual heating degree-days, base 65°F). At one PG&E site (G12.1), space heating usage increased in four of 32 households during the heating season following the retrofit. The coefficient of variation (CV) is 1.07 in this group of homes. In contrast, the CV is 0.64 in the Michigan buildings, suggesting less variability in energy savings, even though the sample contained more varied building types (e.g., single-family, row houses, duplexes) than the California study. There is little information available on occupant behavior in either study but we suspect that differences in indoor temperature preferences contribute to the greater variability in energy savings in the

* The coefficient of variation is defined as the ratio of the standard deviation to the sample mean; a low CV, 0.2-0.4, means that there is less variability in savings.

mild climate.

Predicted versus Measured Savings

Energy audits were performed in some retrofit projects and used in building energy analysis models to estimate potential energy savings. The agreement between model predictions and actual metered consumption is affected by the quality of data available on building characteristics, weather, and occupant life-style, the varying skills of the input preparer, and the ability of model algorithms to model physical processes and account for effects of occupant behavior. There has been relatively little verification of building energy analysis models in occupied buildings or analysis of the consistency and quality of energy audits (Wagner 1984).

Each data point in Figure 6 represents results averaged for a group of houses; note that the variance for individual houses is considerably larger. The sample size for utility program evaluations ranges from 100 to 6300 homes, while it is generally much smaller in research studies (between 1 and 13 homes in six U.S. studies and from 25 to 140 homes in a Swedish experiment). In two of the studies (E9 and E11), the predictive methods were revised after early predictions were compared to metered data (arrows show the relationship between initial and revised predictions). Measured energy savings in utility-sponsored programs fell short of predictions in five of eight projects. The opposite trend is observed in research studies; actual savings exceed prediction estimated in nine of 15 cases. An important point to note is that most research studies were not "blind" simulations, as input preparers typically knew pre- and post-retrofit measured energy use. In contrast, in utility-sponsored programs, participants received a home energy audit estimating energy savings from various measures prior to retrofit. Hence, models are being evaluated under "normal" field conditions, e.g., utility auditor with access to previous utility bills but not to detailed measurements.

Some interesting trends emerge when actual vs. predicted data for individual buildings were analyzed. A Washington utility found that the type of electric heating system in the weatherized home influenced the accuracy of the original savings estimate. Actual savings were 76% of the original estimate in homes with a forced air system but only 38% in homes with baseboard heat. The utility also noted that their predictive model had greater difficulty in accurately estimating savings in homes that installed several measures. Actual savings slightly exceeded predicted estimates when only one measure was installed but were only 44% of estimated savings when five measures were implemented.

DISCUSSION

In discussing measured results from retrofit efforts in residential buildings, it is also worth mentioning several key limitations and gaps in the available data.

It is difficult to accurately estimate space heat savings when given only total billed energy use before and after a retrofit. Program evaluations rarely relied on submetered heating energy use or monitoring of inside temperatures. The absence of such monitoring techniques means that changes in the household appliance stock, use of secondary heating equipment, or adjustments in occupant behavior might have gone undetected, masking the actual effect of the retrofit. At a minimum, program evaluations should include a telephone or on-site survey of occupants in order to obtain information on these issues, a technique used in only a fraction of the studies. A standardized energy audit form (such as that developed by ASHRAE) would also be very useful. Consistent, detailed building descriptions would then be available, making it much easier to account for physical differences among houses prior to retrofit.

It is also important to note that energy savings are based in most cases on only one year of energy use data after a retrofit. Measured data on the persistence of energy savings over multi-year periods are needed in order to validate engineering estimates of retrofit lifetimes, a factor that can be as crucial to cost-effectiveness as first-year savings. Long-term tracking of occupied buildings, however, magnifies the problem of accounting for changes in operating conditions, occupancy, or the effect of additional retrofits. Successful projects will almost surely require direct monitoring of major household end-uses and inside temperatures.

The reported results on retrofit efforts in multifamily buildings should be viewed as preliminary findings. We are hesitant to generalize results for this sector based on data from 28 buildings, particularly given the regional and demographic bias in the sample (e.g., 50% from public housing projects). Successful retrofit strategies noted in this study must be tested in other climatic regions and in varying building types. At present, additional data are being collected on retrofits in multifamily buildings, with emphasis on effective heating and hot water system measures for specific heating system types. We also believe that additional research is necessary on the optimal combination of shell and system measures for various building types and climates.

Finally, it is worth noting the absence of measured data on the effect of retrofits on peak power and cooling energy requirements. It has been difficult to obtain data from regions of the country (i.e., Southeastern and Southwestern U.S.) where cooling accounts for a substantial portion of total residential energy use.

CONCLUSIONS

Key findings from this compilation of current retrofit experience in existing residential buildings are shown in Table 2. Energy savings occurred after retrofit in almost all retrofit projects, with average annual savings ranging from 26 to 38 MBtu (27-40 GJ) in the four categories. Savings actually achieved were typically 20% to 30% of pre-retrofit space heating energy use. These results suggest that most efforts to date have fallen far short of estimates of the identified technical potential. There is substantial variation in energy savings for investments of the same magnitude, even after controlling for pre-retrofit energy intensity, building type (e.g., single- vs. multifamily), and climate. We suspect that the variance in savings is due mainly to differences in occupant behavior, physical differences among houses prior to retrofit, variations in product and installation quality, and to measurement error.

Predicted savings tend to exceed measured results in large-scale conservation programs. The scatter in actual versus predicted data for individual houses is much greater than that for groups of occupied buildings.

The average investment in multifamily buildings is approximately $700/unit, far lower than the average of $1350 spent in single-family residences. Many conservation measures are attractive economic investments from a homeowner's perspective, compared to other investment possibilities. The median real rate of return ranged from 6% in the 30 low-income weatherization projects to 25% in 19 utility-sponsored programs. These rates compare favorably with real rates of return from tax-free bonds (3%-5%).

This study is part of an on-going project (BECA); data contributions from readers are welcomed.

ACKNOWLEDGMENTS

The work described in this report was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

Claridge, D.E.; Jeon, H.S.; Bida, M. and Zwack W. 1984. "Performance Analysis of the Colorado 50/50 Retrofit Program: Volume I." University of Colorado Department of Civil, Environmental, and Architectural Engineering, Boulder, CO.

Crenshaw R., and Clark, R. E. 1982. "Optimal Weatherization of Low-Income Housing in the U.S.: A Research Demonstration Project." National Bureau of Standards Building Science Series 144, Washington, DC.

Dutt, G.S.; Lavine, M.L.; Levi, B.; and Socolow, R.H. 1982. "The Modular Retrofit Experiment: exploring the house doctor concept." PU/CEES #130, Center for Energy and Environmental Studies, Princeton, NJ.

Energy Information Administration (EIA). 1983a. "1982 Annual Energy Outlook: with Projections to 1990." DOE/EIA-0383(82), Washington, DC.

Energy Information Administration. 1983b. "Regression Analysis of Energy Consumption by End Use." DOE/EIA-0431.

Fels, M. F. 1984. "The Princeton Scorekeeping Method: An Introduction." *Energy and Buildings*, (forthcoming).

Goldman, C. A. 1985. "Measured Energy Savings from Residential Retrofits: Updated Results from the BECA-B Project." *Energy and Buildings*, Vol. 8, No. 2, pp. 137-155.

Hoppe, R. J., and Graves, W. L. 1982. "Field Test of Refit Equipment for Residential Oil-fired Heating Equipment." BNL-51555, Brookhaven National Laboratory, Upton, NY.

Katrakis, J. T. 1984. "Documented Energy Savings in Multi-Unit Housing with Emphasis on Efficiency Improving Measures for Existent Space Heating Systems." in *What Works: Documenting Energy Conservation in Buildings*, J. Harris (ed), American Council for an Energy-Efficient Economy.

Office of Technology Assessment. 1982. *Energy Efficiency of Buildings in Cities*, OTA-E-168, Washington, DC.

O'Regan, B.C.; Wagner, B.S.; and Dickinson, J.B. 1984. "Results of the Walnut Creek house doctor project." *Energy*, Vol. 9, No. 1, pp. 75-86.

Wall, L.W.; Goldman, C.A.; Rosenfeld, A.H.; and Dutt G.S. 1983. "Building Energy Use Compilation and Analysis (BECA). Part B: Retrofit of Existing North American Residential Buildings." *Energy and Buildings*, Vol. 5, pp. 151-170.

Wagner, B.S. 1984. "Comparisons of Predicted and Measured Energy Use in Occupied Buildings." *ASHRAE Transactions*, Vol. 90, Part 2.

Williams, J. M. 1980. "An analysis of heating savings for homes retrofitted with ceiling insulation in San Joaquin Division." Pacific Gas & Electric Internal Report.

TABLE 1

Cost-Effective Retrofit Strategies

Sponsor	Location	# of Homes	Retrofit[a] Measure	Space Heat Energy Savings (GJ/yr)	(%)	SPT (yr)	IRR (%)
TVA	Tennessee	105	IA (R-30)	49.8	33	2.2	58%
TVA	Tennessee	546	IA (R-30)	26.8	22	5.1	27%
PG & E	Bakersfield, CA	33	IA (R-19)	15.7	18	5.7	25%
PG & E	Fresno, CA	16	IA (R-19)	20.6	32	4.3	33%
Public Service Co.	Colorado	33000	IA (R-30)	20.7	16	5.1	41%
Consol. Gas	Detroit, MI	71	IA (R-19)	34.5	17	4.2	34%
Univ. of Illinois	Champaign, IL	12	IA (R-30), IW[b]	42.4	30	8.2	20%
Seattle City Light	Seattle, WA	321	WH	5.6[c]	4	3.8	34%

[a] Measure Code: IA=attic insulation; R-19 added to uninsulated home and R-30 means homes brought up to that level, IW=wall insulation, WH= water heater insulation

[b] Five of 12 houses installed wall insulation.

[c] Domestic Hot Water Savings: Percent savings reflects reduction in total electricity use.

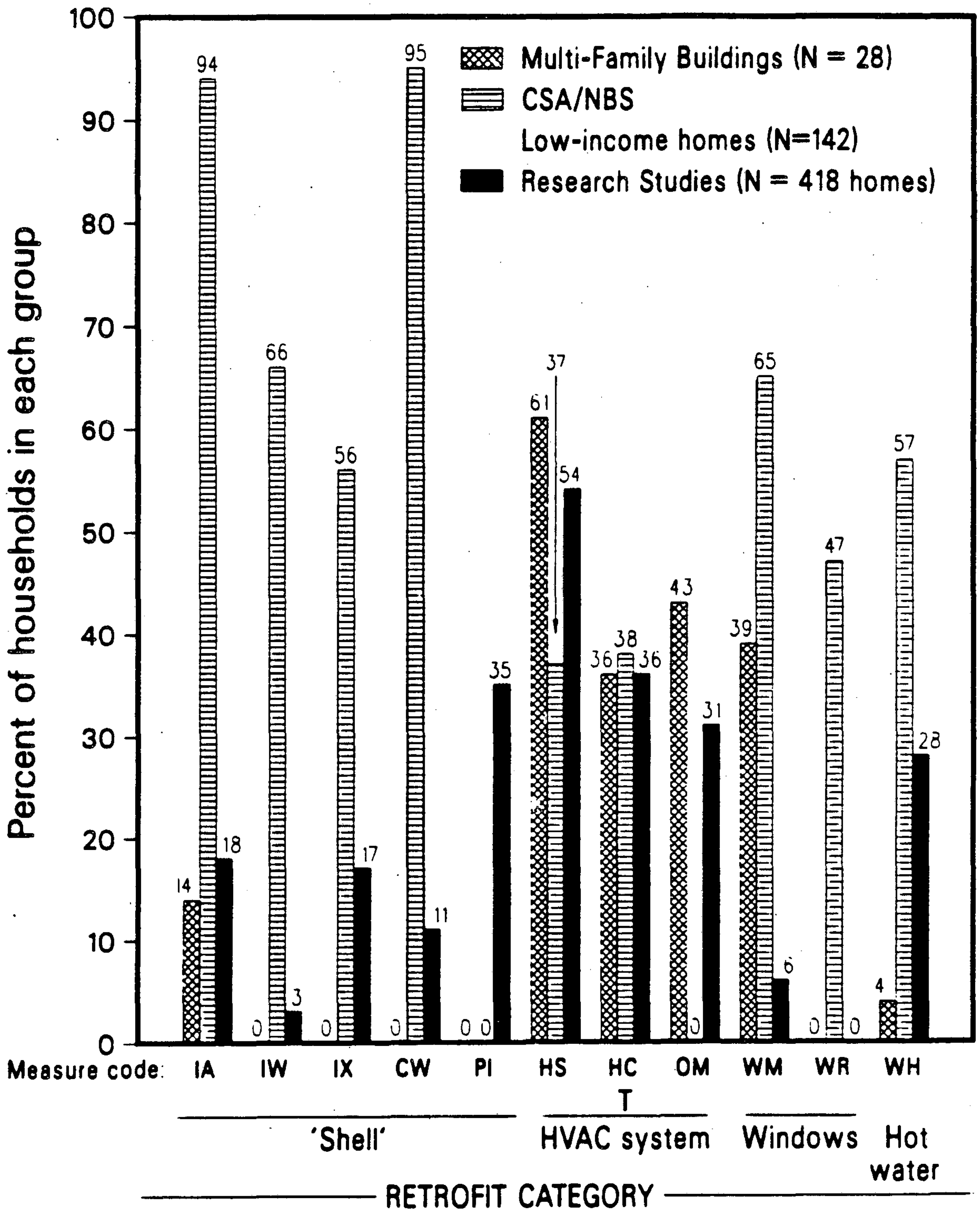
TABLE 2

Summary of Key Findings

		Utility Programs	Low-Income Programs	Research Studies	Multi-Family Buildings
1. Sample Size		N = 19, comprising 43730 homes	N = 30, comprising 938 homes	N = 38, comprising 352 homes	N = 28 bldgs.
2. Cost of Retrofit (1983$)	-Median	705	1370	824	533
	-Average*	1044 ± 702	1578 ± 863	1685 ± 2747	695 ± 551
3. Space Heat Savings (GJ/Yr)**	-Median	38.4	30.5	27.8	15.1
	-Average	40.3 ± 21.0	37.8 ± 26.2	34.3 ± 24.4	27.0 ± 27.4
4. Space Heat Savings (%)	-Median	24%	22%	22%	22%
	-Average	26 ± 11%	24 ± 12%	25 ± 14%	26 ± 14%
5. Simple Payback Time (Yrs)	-Median	5.7	9.2	6.4	4.7
	-Average	10.3	11.4	9.5	7.9
7. Internal Rate of Return (%)	-Median	25%	6%	17%	11%
	-Average	23 ± 15%	13 ± 14%	31 ± 35%	27 ± 31%

* Mean ± standard deviation

** Electric space heat savings are measured in resource energy units, 12.1 MJ/kWh



XCG 839-7234 A

Fig. 1. Relative frequency with which retrofit measures were installed in research studies, multi-family buildings, and CSA/NBS low-income homes. The measure code key is: IA, attic insulation; IW, wall insulation; IX, insulation of miscellaneous areas or unspecified; CW, caulking and weatherstripping; PI, infiltration reduction using blower door pressurization; HS, heating system improvements; HC or T, HVAC controls or clock thermostats; OM, operations and maintenance actions; WM, window management; WR, window repair or replacement; WH, water heating.

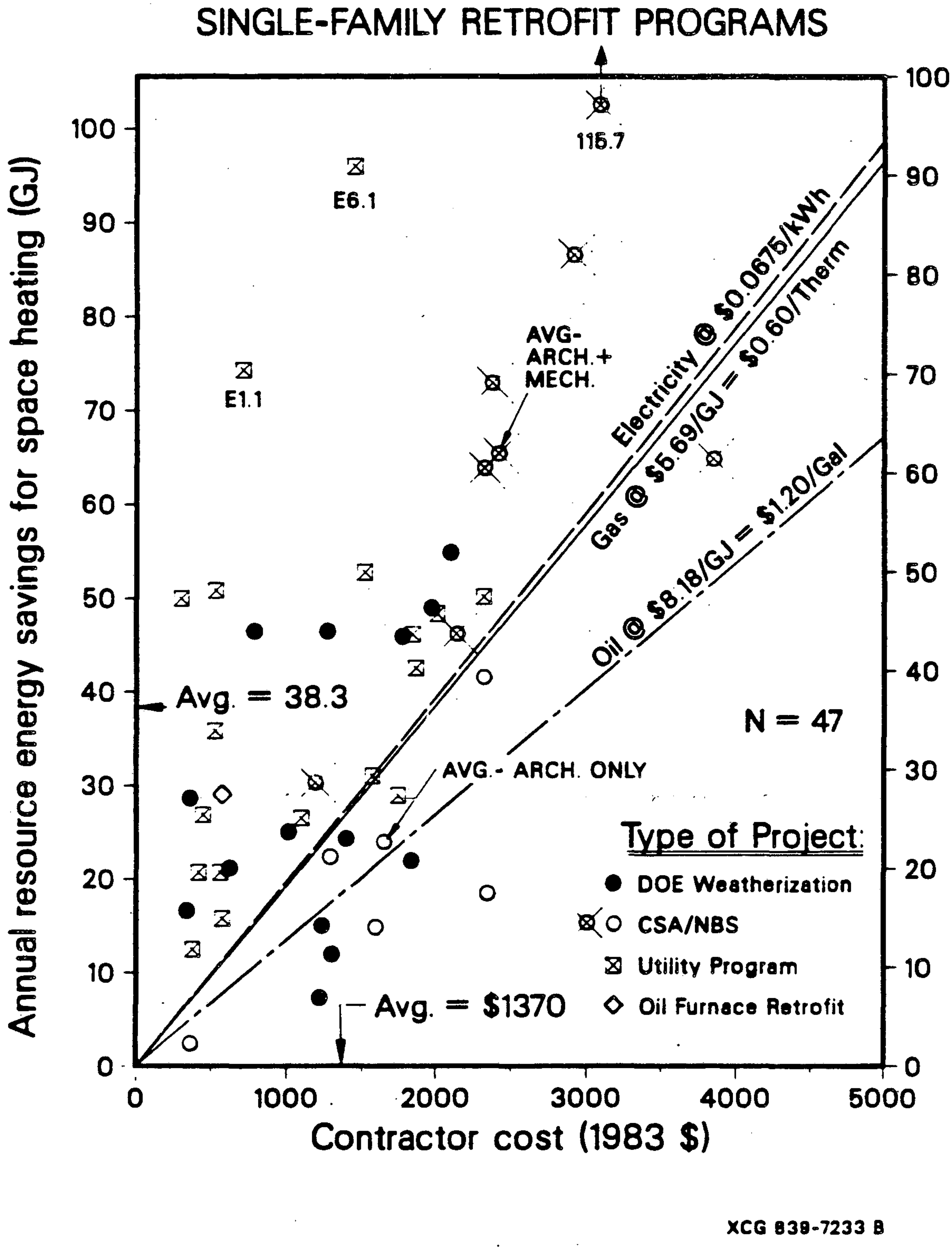


Fig. 2. Annual space heat energy savings are plotted against the first-cost of the retrofit for utility-sponsored and low-income weatherization programs. The data points represent results from 44,000 homes. The sloping reference lines show the minimum energy savings that must be achieved for each level of investment if the retrofit is to be cost-effective compared to national average fuel and electricity prices. This minimum is calculated as the present value of the energy purchases that would be necessary if the retrofit was not installed, assuming a 15-year lifetime, constant (1983$) energy prices, and a 7% real discount rate. Electricity is measured in resource units of 11500 Btu/kWh (12.1 MJ per kWh).

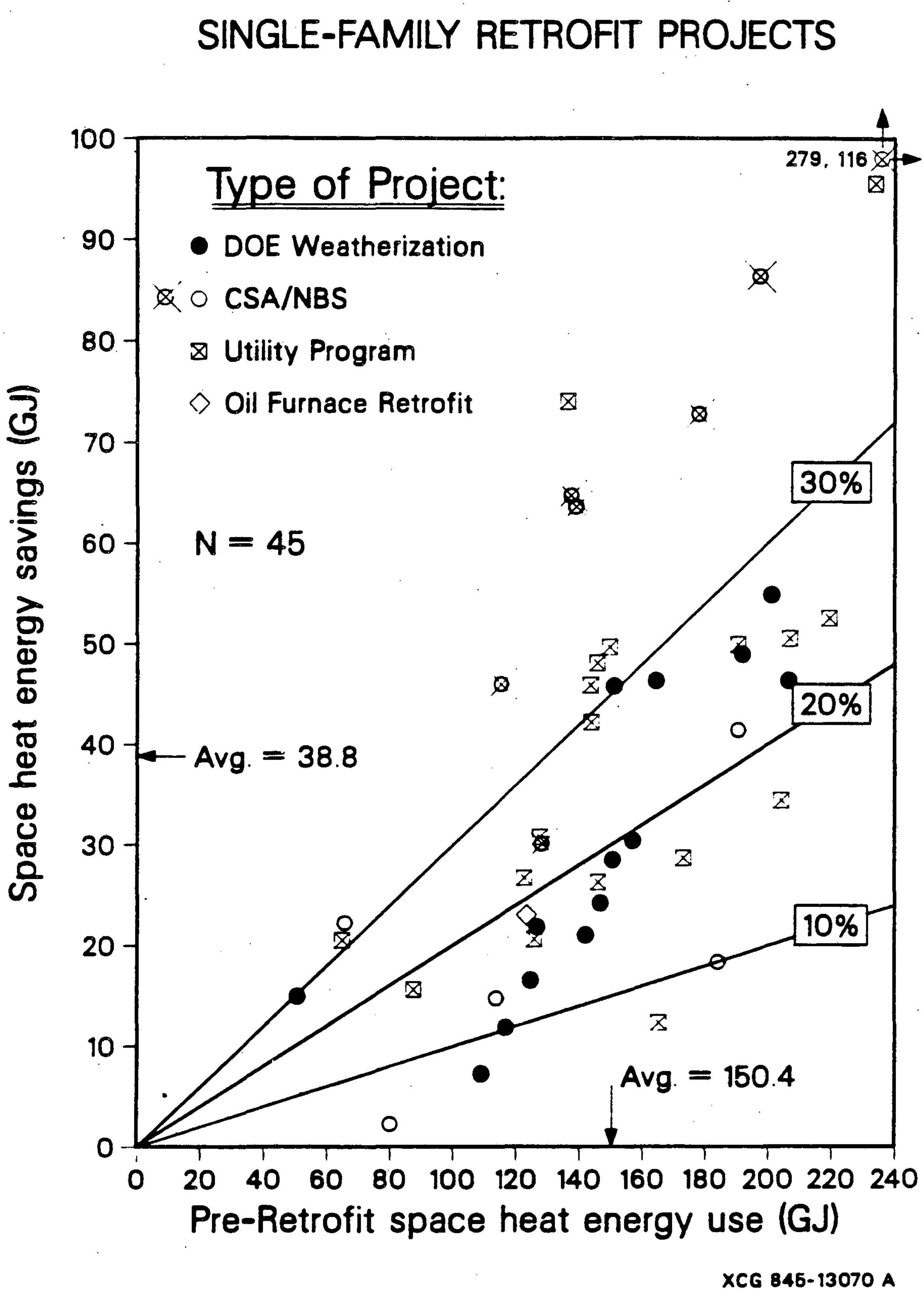


Fig. 3. Annual space heat energy savings as a function of pre-retrofit space heat energy use in 45 single-family retrofit projects. Electricity use is expressed in terms of site energy, 3413 Btu per kWh, (3.6 MJ per kWh).

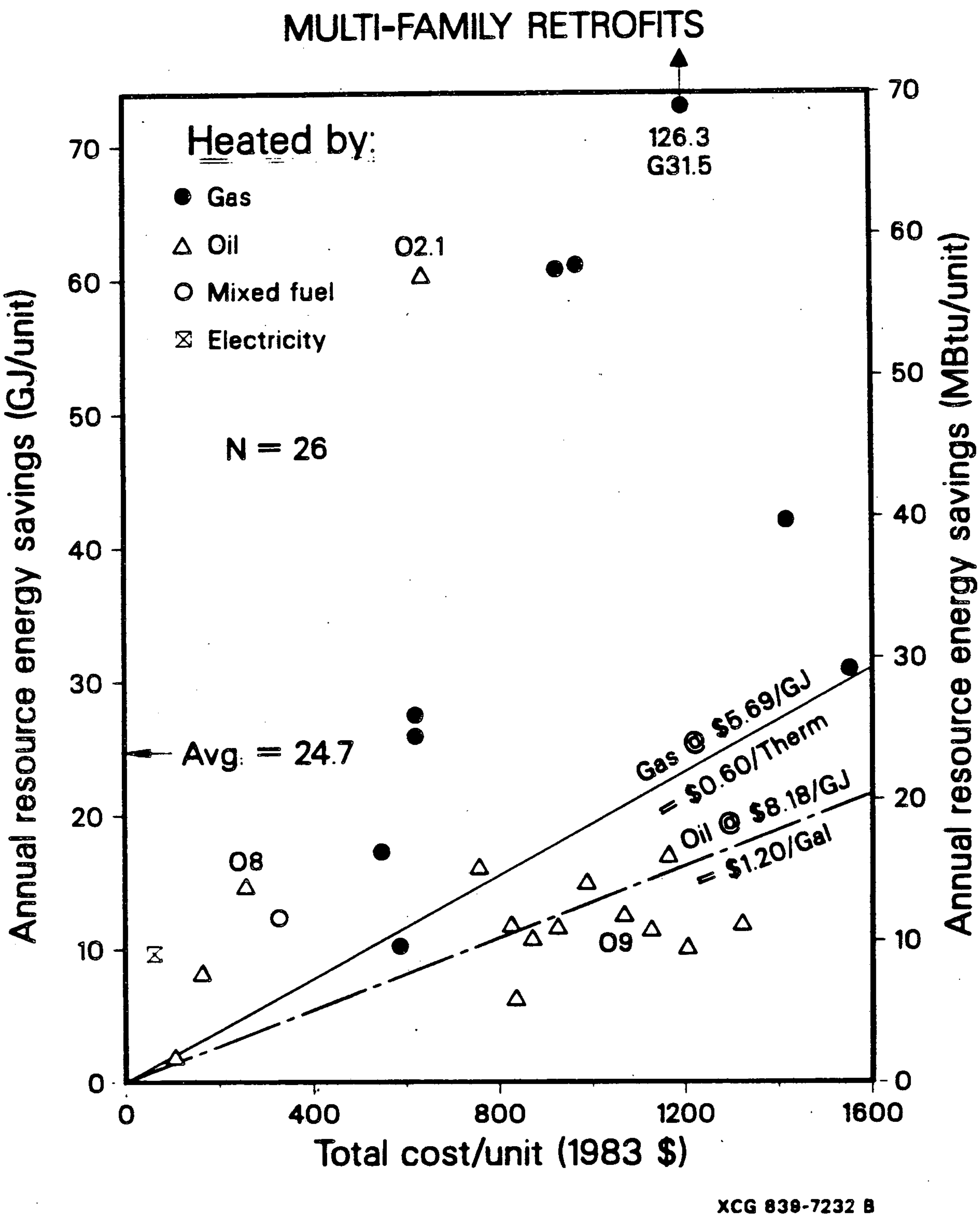


Fig. 4. Annual resource energy savings are compared to the total cost of the retrofit investment in 26 multifamily buildings. Savings and costs are divided by the number of apartment units in that building. In most cases, the savings apply to space heat only, except for five buildings where the retrofit addressed both space heat and domestic hot water usage. Estimated annual maintenance costs are included in the total cost. Price reference lines are defined as in Fig. 2. Electricity is measured in resource units, 11500 Btu per kWh.

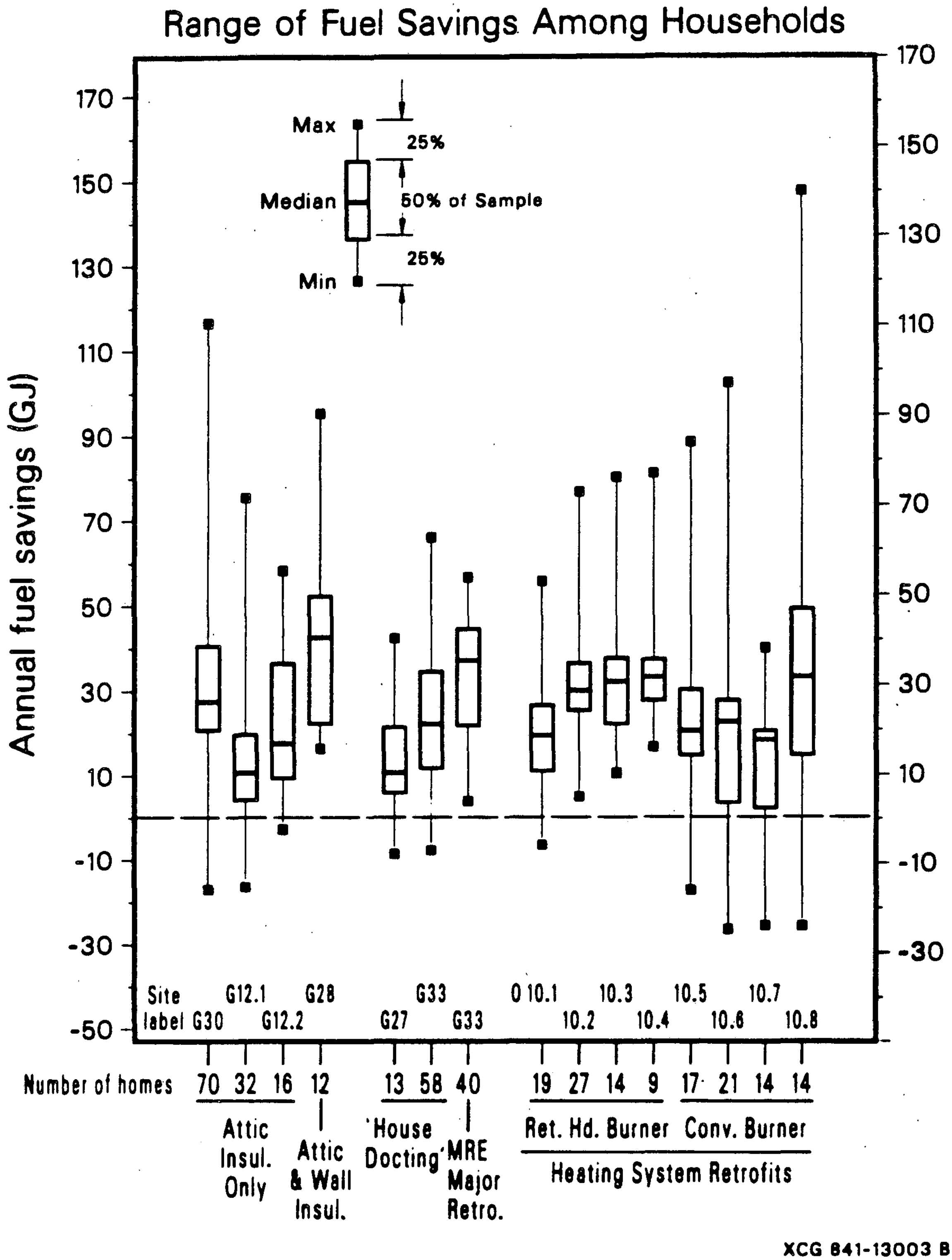


Fig. 5. Range in annual fuel savings among households installing similar measures. In most cases, the savings apply to space heat only, except for the heating system retrofits and the "house-doctor" experiments where consumption includes all end-uses of the space heating fuel.

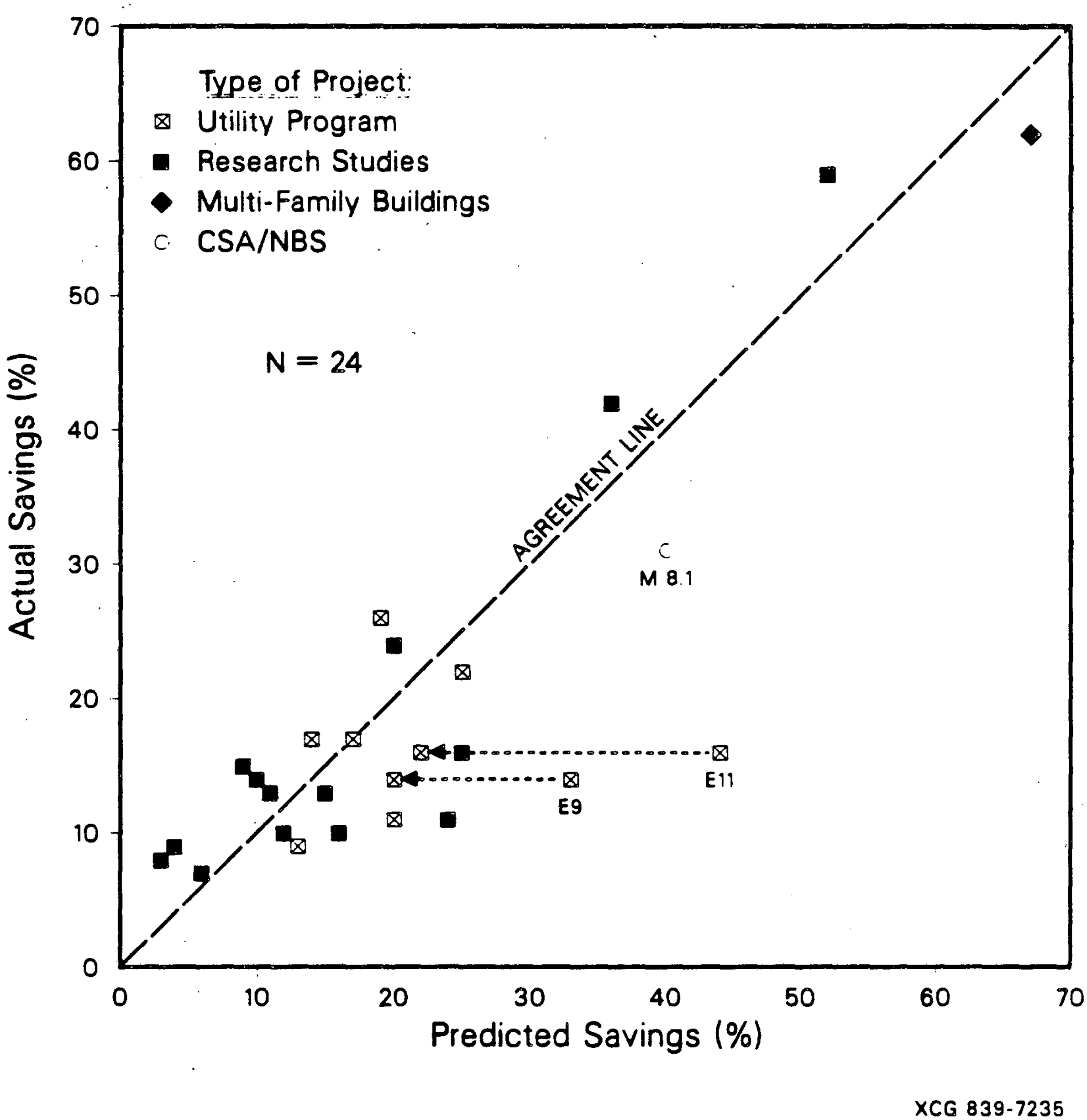


Fig. 6. Actual versus predicted savings plotted by type of retrofit project for 24 studies. The dashed lines (E9 and E11) indicate revised predicted savings from initial comparisons with metered data.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720