

## ENERGY SAVINGS IN RETROFITTED MULTI-FAMILY BUILDINGS: NEW RESULTS FROM THE BECA-B PROJECT

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### ABSTRACT

We compile and analyze measured data on 141 retrofit projects in U.S. and Swedish existing multi-family buildings. We examine the costs of conservation measures and practices and the savings they generate. We also discuss the correlation between energy savings and initial pre-retrofit energy intensity, amount of investment, and choice of measures.

Various HVAC system retrofits (heating controls, equipment measures, and altered operation and maintenance practices) are the most popular conservation strategies in our sample of buildings. Most buildings in the data base are small to medium size multi-family buildings; 60 percent are between 10 and 50 units; only 10 percent are more than 100 units. Retrofit costs are less than \$250/unit in 40 percent of the buildings, which suggests that many building owners confined their retrofit efforts to fairly low-cost measures. On average, initial retrofit costs are a lower fraction of annual energy expenditures in our sample of U.S. buildings than in our Swedish buildings (0.6 versus 2.1).

Median annual energy savings are 11 MBtu per dwelling unit, or 16% of pre-retrofit energy use. Energy savings are between 10 and 30 percent in 60 percent of the retrofit projects. We found that categorizing each retrofit project by strategy helped explain much of the variation in the amount invested; however, energy savings still varied widely among similar groups. Preliminary results for buildings in the data base suggest that some envelope measures (e.g., "shell" packages and window measures) have longer payback periods (12 and 16 years, respectively) than many of the heating system retrofit strategies (1-3 years). We also report on individual conservation measures that are particularly effective in specific building and heating system types (e.g., outdoor resets for cold-climate buildings with hydronic boilers).

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## INTRODUCTION

The multi-family sector, consisting of residential buildings with two or more units, comprises almost 27 percent of the U.S. housing stock (in terms of household units). Annual site energy use in these buildings is approximately 2.3 quads (1 quad =  $10^{15}$  Btu) and directly or indirectly costs U.S. households almost \$20 billion. Multi-family buildings vary widely in construction complexity, from single-family style to large office-building type structures. A recent Office of Technology Assessment study estimated the conservation potential in the multi-family sector at 1.0 quad per year by the year 2000 (43% of the sector's current energy use), although likely savings were only 0.3 quad, because of complex technical, information, institutional, and economic barriers (OTA, 1982). A 1985 survey of organizations concerned with multi-family retrofit activity highlighted some of these barriers:

- unwillingness on the part of building owners to invest in costly measures without guaranteed savings,
- problems related to split in economic interest between landlords and tenants,
- difficulty in obtaining financing for retrofits, and
- conflicting information on the performance and costs of retrofits (DOE, 1985).

The study and survey also found that documented information on the results of energy-efficiency improvements is not widely available. We attempt to address this problem by compiling and analyzing measured data on the costs of conservation measures and practices in multi-family buildings, and the energy savings they produce.\* In this study, we examine the correlation between energy savings and initial pre-retrofit energy intensity, amount of investment, and choice of measures. We also identify individual measures that are effective for specific building and heating system types, and discuss limitations and gaps in the available data.

## DATA SOURCES

We obtained information on retrofit projects from several data sources, including city energy offices [40], public housing authorities [40], research institutions and national laboratories [25], private building owners/managers [16], non-profit and for-profit energy service companies [14], and utilities [3].† The data collected typically included metered energy consumption, installed retrofit measures and their costs, the price of the space heating fuel the winter after retrofit, and a brief description of the physical characteristics of the building. In most cases, each data point represents one building, except in the case of public housing projects, which often have a number of buildings on one utility master meter.

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\* Results are drawn from the Buildings Energy Use Compilation and Analysis (BECA) residential data base at the Lawrence Berkeley Laboratory.

† Numbers in brackets represent number of data points obtained from each source.

## BUILDING CHARACTERISTICS AND RETROFIT MEASURES

Most buildings in the data base are small to medium size multi-family buildings; 60 percent are between 10 and 50 units; only 10 percent are more than 100 units (Table I). Apartment size is comparable to the national multifamily stock; floor area per dwelling unit is between 500 and 1000 ft<sup>2</sup> in 70 percent of the buildings. Almost all of the buildings have central heating systems and are master-metered. Eighty-five percent are occupied by renters. Gas is the dominant space heat fuel (53%), followed by fuel oil (23%).

The sample of buildings in the data base is somewhat skewed with respect to geographic location, with clusters of buildings in a few cities/regions. For example, 40 buildings are located in the Minneapolis-St. Paul area, 50 retrofit projects are in the New York City-New Jersey area, and 11 projects are in San Francisco. Most of the U.S. buildings can be grouped into three categories:

- 10-30 unit, low-rise, wood-frame buildings built in the 1950's or 1960's with hydronic heating systems,
- steam-heated, low-rise buildings (typically 3-story walk-ups) with masonry bearing walls constructed between 1910 and 1940,
- high-rise public housing projects built in the 1940's or 1950's with 40 to 100 units in each building.

In general, multi-family retrofits were directed toward reducing consumption in the largest end-uses: space heating and domestic water heating. The most popular conservation strategies in our sample of buildings were various HVAC system retrofits including (Fig. 1):

- heating system controls, such as outdoor resets, high limit outdoor cutout, and thermostatic radiator vents,
- heating system equipment measures, including new burners and vent dampers,
- boiler replacements,
- altered operation and maintenance practices.

Window retrofits were common measures, usually either storm windows or double-glazed thermal break aluminum windows. Typically, the cost per dwelling unit for these measures was high (\$500 - 1200/unit); building owners and tenants often justified the cost by citing additional benefits of these retrofits, including improved building appearance, increased security, and decreased maintenance expenses. In general, envelope measures were implemented far less frequently than heating system measures in U.S. buildings, in contrast to our small sample of retrofitted Swedish buildings, in which envelope and HVAC system measures were equally popular. Some shell measures (e.g., wall insulation) may be implemented less often because of the physical characteristics of many multi-family buildings (e.g., masonry walls), which make the measures difficult to install.

Initial retrofit costs were less than \$250/unit in 40 percent of the buildings, which suggests that many building owners confined their retrofit efforts to fairly low-cost measures (Fig. 2). The median cost of the retrofits was \$537/unit for all buildings in the data base; costs were much higher (\$1100/unit) in the Swedish buildings. We calculated the ratio of retrofit costs to pre-retrofit energy expenditures (in local currency) in order to derive an indicator that was not influenced by exchange rates altering over time. For Swedish buildings, the median cost of the retrofit was 2.1 times greater than annual energy expenditures prior to retrofit, compared to a ratio of only 0.6 for U.S. buildings. Sweden's larger investment is not surprising since the retrofits were part of government-sponsored research projects designed explicitly to evaluate the savings and cost-effectiveness of combinations of retrofit measures.

## APPROACH

In most cases, we (or our data source) used the Princeton Scorekeeping Method (PRISM) to analyze energy consumption data before and after retrofit.\* PRISM estimates a weather-normalized annual energy consumption (NAC) from parameters obtained from a regression of either utility bill or meter readings of the space heat fuel and daily average outdoor temperature (Fels, 1986). The NAC represents consumption that would occur in a year with typical weather conditions.

We were not able to use PRISM in 50 projects because of data problems (e.g., insufficient number of actual meter readings, monthly energy data without billing dates, or only annual energy consumption data provided). In these cases, we corrected for the varying severity of winter in different years by scaling annual estimated space heat energy consumption using the ratio of normal-to-actual year heating degree-days (base 65°F). Annual baseload energy use was calculated by scaling estimated summer fuel use to a full year. In most of these cases, summer fuel use was estimated by building owners.

For purposes of comparison, energy use at each project is expressed on a per dwelling-unit basis. In multi-family buildings, tenant turnover is often high and occupancy rates vary greatly over time. Energy savings may be masked by increases or decreases in the number of occupied units after a retrofit. For example, it is reasonable to assume that increases in the number of occupied units (and presumably occupants) will cause an increase in hot water and appliance energy use as well as heating load (depending on heating system type, distribution and control system, and operation and maintenance practices). For the 35 buildings where we were able to obtain information on vacancy rates, we divided energy use during each billing period by the number of occupied units in that period to adjust for this effect.

Retrofit costs reported in this study reflect the direct costs to the building owner of contractor-installed measures. The costs are calculated in constant dollars (1985\$). Costs and energy prices for European buildings were converted at 1981 exchange rates to U.S. dollars; U.S. inflation rates were used to convert to constant dollars.\*\* We calculate two economic indicators: simple payback time (SPT) and internal rate of return (IRR). SPT is the period required for the undiscounted value of future energy savings (at today's energy prices) to equal the initial cost of the retrofit. The IRR is the rate of interest which, when used to discount the life-cycle costs and savings of an investment, will make the two equal. The IRR calculation includes estimated annual operations and maintenance costs. We also assume that residential energy prices will escalate annually at a real rate of 1 percent over the measures' expected physical lifetime, based on recent Energy Information Administration (EIA, 1986) forecasts of average residential energy price increases (weighted by consumption) over the next ten years.

## RESULTS

### *Energy Savings*

Median annual energy savings for buildings in the data base were 11.2 MBtu ( $10^6$  Btu) per dwelling unit, or 16 percent of pre-retrofit energy use. Energy savings were between 10 and 30 percent of pre-retrofit use in 60 percent of the projects; weather-normalized consumption increased after retrofit in 5 percent of the buildings (Fig. 3). Prior to retrofit, annual consumption of the space heat fuel (adjusted for floor area) is noticeably higher in the sample of buildings owned and managed by public housing authorities (PH) compared to Swedish and other U.S. multi-family buildings (mostly privately owned). This trend is most evident in low-rise buildings and is rather pronounced when we note that the public housing projects in the data base are located in climates with fewer heating degree-days than other multi-family buildings (Fig. 4). Within each climate zone, most buildings in this study used more energy before retrofit than the respective stock average for U.S. gas- and oil-heated multi-family buildings.†

\* LBL analyzed utility billing data (when available) in all projects except those conducted by the Minneapolis Energy Office and Princeton Center for Energy and Environmental Studies, who did their own PRISM analysis.

\*\* We used 1981 exchange rates because most experts believe that in more recent years the dollar has been overvalued with respect to other major currencies.

† We used the 1982 RECS public use data tape to calculate energy consumption/ft<sup>2</sup> of the space heat fuel for gas and oil-heated multi-family buildings with five or more units. To estimate a stock average, we weighted energy use/ft<sup>2</sup> in four climate zones by

Energy savings are correlated more strongly with energy consumption before retrofit ( $r = 0.68$ ) than with total cost of the measures ( $r = 0.37$ ). We found that categorizing each retrofit project by strategy helped explain much of the variation in the amount invested; however, energy savings still varied widely among similar groups (Fig. 5). Various types of heating system controls were the most popular low-cost strategy, while structural renovation of the building envelope, boiler replacement/retrofit and heating distribution system conversions (both indicated by dark square) and window retrofits were the most costly (i.e., greater than \$1000/unit). In most cases, investments in excess of \$2000/unit do not save enough energy to justify the cost. The 22 projects that invested over \$2000/unit had a median payback time of 20 years.

Results from buildings in the data base suggest that some envelope measures (e.g., shell packages and window measures) have much longer payback periods than many of the heating system retrofit strategies (see Fig. 6 and Table II). However, the apparently superior economics of heating system measures may not persist over time. Typically, the success of most of the heating system measures is more closely linked to ongoing operating and maintenance practices (which can be problematic over the long term) than envelope retrofits.\* There are other important differences between these groups of buildings:

- median energy use before retrofit was lower in the group of buildings that received window and shell retrofits and heating controls (50-65 MBtu/unit) than in buildings that installed energy management control systems (EMCS) and heating system measures (90-110 MBtu/unit),
- the groups differ with respect to climate severity; buildings that received window and shell measures (5000 HDD) are located in milder climates than the buildings that received heating system measures (7000 HDD),
- individual unit electric resistance heaters were used in 25% of the buildings that received shell retrofits (thus precluding many of the system retrofits),
- all window retrofits were installed in high-rise buildings, while retrofits in the other four groups were implemented principally in low-rise buildings.

In summary, two of the groups of buildings which received heating system retrofits were also located in more severe heating climates and were relatively more energy-intensive before retrofit than groups that received shell and window measures; hence differences in cost-effectiveness are not attributable solely to choice of measures.

A more detailed comparison of groups of similar retrofits is shown in Table II. There is an element of subjectivity in the classification of many retrofit projects, in that sets of often widely assorted measures are implemented at the same time. In some cases, we grouped retrofit projects into one of three broad strategies: 1) heating and hot water system packages, 2) shell packages (e.g., various envelope measures), and 3) system and shell packages. Where possible, we classified a retrofit project into a more disaggregated group (e.g., window measures, heating controls, solar DHW). Energy savings are significant at the 90 percent confidence level for all strategies except energy management control systems (EMCS), boiler replacements and controls, and solar domestic hot water systems (DHW). The savings in buildings that received EMCS and boiler replacements were not significant at this confidence level because our sample was small (4-5 buildings), and savings varied widely.

We believe that it is not appropriate to evaluate metering conversions and boiler replacements in the same context as the other strategies (hence they are separated at the bottom of Table II). Metering conversion projects in the data base involve changing from master metering to tenant metering systems (except for one project). A tenant metering system is not strictly a technical efficiency measure since reduction in energy use is due to changes in occupant behavior. The economics of tenant metering systems appear quite attractive from the perspective of the building owner, based on a sample of 10 low-rise Minnesota buildings which have hot water baseboard heating systems and individual zone control of the

the number of households that heated with each fuel.

\* See Greely et al., "Analyzing energy conservation retrofits in public housing" for discussion on persistence of savings.

flow of hot water into each apartment (Hewett, 1986). Energy costs were included in the rent in these master-metered buildings prior to the installation of the new metering system. The new metering system divides the energy bill among individual apartments on the basis of use. After the new system was installed, gas energy use decreased by 15-18 percent compared to pre-retrofit levels. The effect of tenant metering on the individual tenants depends on whether or not the building owner reduces rents to account for his lower operating expenses. If this retrofit is implemented without a rent reduction, the tenant's total costs can increase significantly. From a public policy perspective, it is important to ensure that metering systems do not weaken the building owner's commitment to finance future efficiency improvements, and that energy costs are allocated equitably on the basis of actual use (e.g., accurate measurement of delivered heat, and accounting and billing for non-space heating and standby losses).

Installing conservation measures in conjunction with equipment replacement tends to improve the economics of rehabilitating older multi-family buildings, however, this strategy makes it difficult for us to accurately assess the impact of boiler replacement on energy consumption. In most cases, the quality of reported cost and consumption data, makes it impossible to perform a cost/benefit analysis of the merits of boiler replacement versus other retrofit options. The incremental costs associated with installing a new energy-efficient boiler are typically not available, and we can not determine the magnitude of savings attributable to the new boiler because other measures (e.g., storm windows) are also installed. Not surprisingly, total costs are high for this group of buildings (over \$2000/unit), thus payback times are long (12-17 years) despite significant energy savings (21 to 26 MBtu/unit).

#### *Individual Measures*

Typical retrofit practice is to install a set of measures concurrently, although we have compiled data for a subsample of buildings in which individual measures were implemented. For example, the Minneapolis Energy Office (MEO) monitored energy consumption in nine, low-rise apartment buildings with gas-fired hydronic boilers that received outdoor reset and cutout controls (Hewett, 1984). These three-story walk-ups are all master-metered, with wood-frame construction, lightly insulated walls and roofs, and double-glazed windows. Initial retrofit costs were quite low (\$10-20/unit), space heat savings were significant (approximately 13 percent), and paybacks were very short (roughly one year). The results suggest that an outdoor reset is probably the most cost-effective retrofit for hydronically heated apartment buildings with cast-iron boilers.

The MEO also tested and monitored the effectiveness of a set of measures designed to balance the heat distribution system in buildings with single-pipe steam systems. Uneven heating is a common problem in steam-heated buildings and is caused mainly by large differences in steam arrival times among radiators in a building, excessively short boiler cycles, and the absence of individual unit temperature controls (Peterson, 1984).<sup>\*</sup> The steam balancing techniques employed in this group of ten buildings included: 1) installation of larger main-line air vents (to reduce the differences between steam arrival times at near and far radiators), 2) new boiler controls which effectively lengthen the boiler cycle, and 3) thermostatic radiator vents (to improve individual space temperature control) (Peterson, 1986). Boilers were cleaned and tuned at three of the sites. Annual gas savings averaged 10 MBtu/unit among the 10 buildings, roughly six percent of pre-retrofit consumption. Improved comfort is often the primary motivation for this retrofit; therefore, it is not completely surprising that three buildings had negative energy savings (i.e., savings are only expected to occur if the indoor temperature averaged over all of the units decreases). Payback times ranged from one to five years for the seven buildings that realized savings.

## DISCUSSION

The typical master-metered multi-family building has unique characteristics which pose challenges for analysts who wish to "keep score" of the effectiveness of conservation programs/measures. Turnover rates are high among U.S. renters (almost half of renters remain in their residences for only one year or

<sup>\*</sup> High indoor temperatures are a by-product of uneven heating, which results in greater conduction and infiltration losses (opening windows to relieve overheating).

less), and 85 percent of the multifamily stock is occupied by renters (DOE, 1985). Evaluations of retrofit programs directed at single-family homes generally exclude homes in which occupancy has changed; this approach is clearly not feasible in master-metered buildings. We do not account for changes in energy use due to possible differences in behavior patterns between occupants who moved into a building after a retrofit, and those who previously occupied the unit. With the current level of monitoring, secondary heating equipment use or occupant behavior changes might go undetected, masking the actual effect of retrofits.

We do normalize energy use by the number of occupied units before and after retrofit (when data are available), although this is at best a crude proxy in accounting for the impact of occupant density and amount of conditioned space on energy use. We assume that vacant units are unheated; this may not be true. Other data reporting problems include missing information on key physical parameters, or inconsistencies in reported information, as is the case for conditioned floor area. A detailed building description and operating profile, possibly one specified by a protocol, would help overcome this problem.

With a few exceptions, retrofit projects in this compilation did not meter heating energy use separately or monitor inside temperatures. Energy savings are based in most cases on only one year of consumption data after a retrofit. Even when energy use data are available, long-term tracking of occupied buildings is difficult, because the problem of accounting for changes in operating conditions, occupancy, or the effect of additional retrofits is magnified as the monitoring period increases.

It is difficult to estimate space heat (or DHW energy) savings accurately when energy data are limited to utility bills from before and after a retrofit. We can, however, report on the overall quality of the PRISM estimates. The mean value of the relative standard error of NAC is roughly 4 percent for multifamily buildings that were analyzed with PRISM, while the standard error of the reference temperature is generally around 4°F.\* In terms of quality of fit, the average coefficient of determination ( $r^2$ ) is 0.95 for all buildings, although the average  $r^2$  is lower (0.88) for buildings located in mild, coastal climates (e.g., San Francisco). It appears that the overall results are somewhat less robust compared to those obtained in gas-heated single-family houses (Dutt, 1986).

## CONCLUSION

We found that energy savings are between 10 to 30 percent of pre-retrofit energy use in 60 percent of the buildings in our compilation. Large variations are observed in energy savings and in costs per unit of energy saved among similar measures. On average, initial retrofit costs are a lower fraction of annual energy expenditures in our sample of U.S. buildings than in Swedish buildings (0.6 versus 2.1). This difference can be partly attributed to two facts: Swedish buildings have lower pre-retrofit energy intensities than American buildings, and also receive relatively costly shell improvements more often than U.S. buildings. Many conservation investments are attractive from a building owner's perspective: the median real rate of return for buildings in this study is 14 percent, which compares quite favorably with real rates of return from tax-free bonds (3-5%). Preliminary results also suggest that, in our sample of multi-family buildings, some envelope measures (e.g., shell and window measures) have longer median payback periods than many of the heating system retrofit strategies.

We are beginning to compile evidence on the effectiveness of individual conservation measures in specific building and heating system types (e.g., outdoor resets for cold-climate buildings with hydronic boilers). There are several on-going research projects (e.g., DOE:LBL, Princeton CEES; Gas Research Institute: Center for Neighborhood Technology; Bonneville Power Administration's ELCAP project) in which detailed monitoring (i.e., energy end-use data and indoor temperature measurements) will be used to assess the performance of selected multi-family retrofits. We plan to use the data from these monitoring projects to improve our understanding of retrofits in which there is only whole-building energy data.

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\* The mean relative standard error of NAC is lower for gas-heated buildings compared to oil-heated buildings (3 vs. 5%).

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

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Table I. Building and demographic characteristics.

	No. of Projects <sup>a</sup>	% of Total Projects		No. of Projects	% of Total Projects
• Building Type:			• Climate Zone: <sup>d</sup>		
High-Rise.....	52	37	1 (> 7000 HDD).....	43	30
Low-Rise <sup>b</sup> .....	82	58	2 (5500-7000 HDD).....	28	20
			3 (4000-5500 HDD).....	58	41
• Heating System Type:			4 (< 4000 HDD).....	12	9
Central.....	127	90	• Occupancy:		
Individual Unit.....	7	5	Family.....	34	24
• Space Heat Fuel:			Senior.....	9	6
Natural Gas.....	75	53	Adults Only.....	11	8
Oil.....	33	23	Mixed <sup>e</sup> .....	48	34
Electricity.....	6	4	• Ownership:		
Mixed Fuel <sup>c</sup> .....	12	9	Renter-Occupied.....	118	84
District Heating.....	15	11	Owner-Occupied.....	13	9
• Size of Dwelling Units:			• Dwelling Units per Building:		
< 500 ft <sup>2</sup> /unit.....	2	1	< 10.....	24	17
500-750 ft <sup>2</sup> /unit.....	28	20	10-25.....	38	27
750-1000 ft <sup>2</sup> /unit.....	71	50	25-50.....	46	33
1000-1250 ft <sup>2</sup> /unit...	19	14	50-100.....	17	12
1250-1500 ft <sup>2</sup> /unit...	4	3	100-150.....	10	7
1500-1750 ft <sup>2</sup> /unit...	4	3	150-200.....	3	2
1750-2000 ft <sup>2</sup> /unit...	4	3	> 750.....	1	1

<sup>a</sup> Total number of projects is 141; information is not available on certain building characteristics.

<sup>b</sup> Low-Rise = 4 stories or less.

<sup>c</sup> "Mixed Fuel" means that either two fuels are used for space heating (typically gas and oil, depending on availability), or that fuel switching occurred after the retrofit.

<sup>d</sup> Climate zones as defined by the Residential Energy Consumption Survey (Energy Information Administration, *Housing Characteristics 1982*, 1984, p. 211).

<sup>e</sup> "Mixed" occupancy projects include a combination of the above categories.

**Table II. Energy savings and cost-effectiveness of various retrofit strategies. <sup>a</sup>**

Retrofit Strategy	Number of Projects [No. of Units]	Median Site Energy Savings (MBtu/unit-yr.)		Median Total Cost (1985 \$/unit)	Median SPT (years)	Median IRR (%)
		(%)	(%)			
Heating Controls	18 [5268]	7 ±3	15 ±4	50 ±60	1.2 ±0.5	89 ±49
System Packages <sup>b</sup>	29 [2117]	11 ±4	13 ±3	170 ±100	1.8 ±1.0	37 ±74
EMCS <sup>c</sup>	5 [2874]	16 ±17	18 ±14	570 ±110	2.8 ±1.4	26 ±38
System and Shell Packages	18 [764]	17 ±9	26 ±5	1260 ±260	7.8 ±7.0	9 ±10
Distribution System Conversion <sup>d</sup>	7 [118]	24 ±13	25 ±5	780 ±1280	8.9 ±3.6	14 ±9
Shell Packages	12 [3840]	6 ±4	4 ±4	280 ±210	11.5 ±6.4	4 ±13
Window Measures	12 [11143]	11 ±2	16 ±2	1090 ±110	16.9 ±2.3	5 ±2
Solar DHW	6 [388]	2 ±4	6 ±6	570 ±20	36.5 ±57.0	0 ±0
Metering Conversion <sup>e</sup>	11 [2983]	11 ±4	18 ±3	230 ±10	1.4 ±0.3	53 ±27
Boiler Replacement & Controls	4 [474]	26 ±17	16 ±9	2430 ±1290	12.9 ±8.4	7 ±9
Boiler Replacement & Windows	7 [393]	21 ±5	18 ±3	2430 ±200	17.2 ±2.2	0 ±0

<sup>a</sup> Results given are median values plus standard error (se) of the sample median. Standard error of the sample median is computed from:

$$se [\text{median}(X)] = IQ(X) / N^{0.5}$$

where IQ is the interquartile range and N is the number of projects.

<sup>b</sup> "Packages" refer to sets of retrofit measures implemented at the same time, so that the savings attributable to individual retrofits cannot be determined. "Systems packages" are retrofits to space heat and hot water systems. "Shell packages" means that various envelope measures were implemented (e.g., insulation, caulking and weatherstripping, storm windows).

<sup>c</sup> EMCS refers to energy management control systems.

<sup>d</sup> At these projects, the heating distribution system was converted from steam to hot water.

<sup>e</sup> The category "Metering Conversion" includes conversion of electricity billing from master-metered to individual unit submetering and installation of tenant metering systems that divide total gas use in an apartment building on the basis of indicators that are proxies for the amount of heat delivered (e.g., number of hours that the thermostat calls for heat).

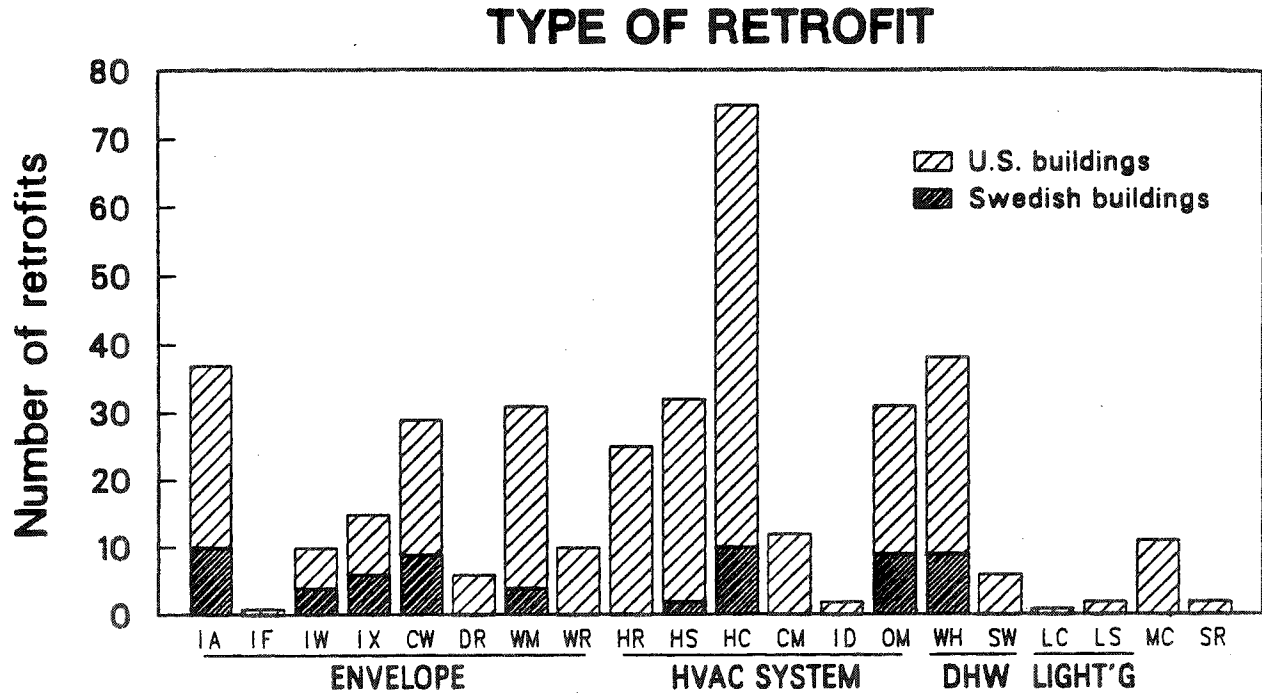


Fig. 1. Relative frequency with which retrofit measures were installed in multi-family buildings. Retrofit code is: IA, attic insulation; IF, floor insulation; IA, wall insulation; IX, general insulation; CW, caulking and weatherstripping; DR, storm doors; WM, window measures; WR, window replacement; HR, heating system replacement; HS, heating system retrofit; HC, heating controls; CM, computerized heating control system; ID, duct insulation, OM, operations and maintenance; WH, water heating retrofit; SW, solar domestic hot water; LC, lighting controls; LS, lighting retrofits; MC, metering conversion; and SR, structural renovation.

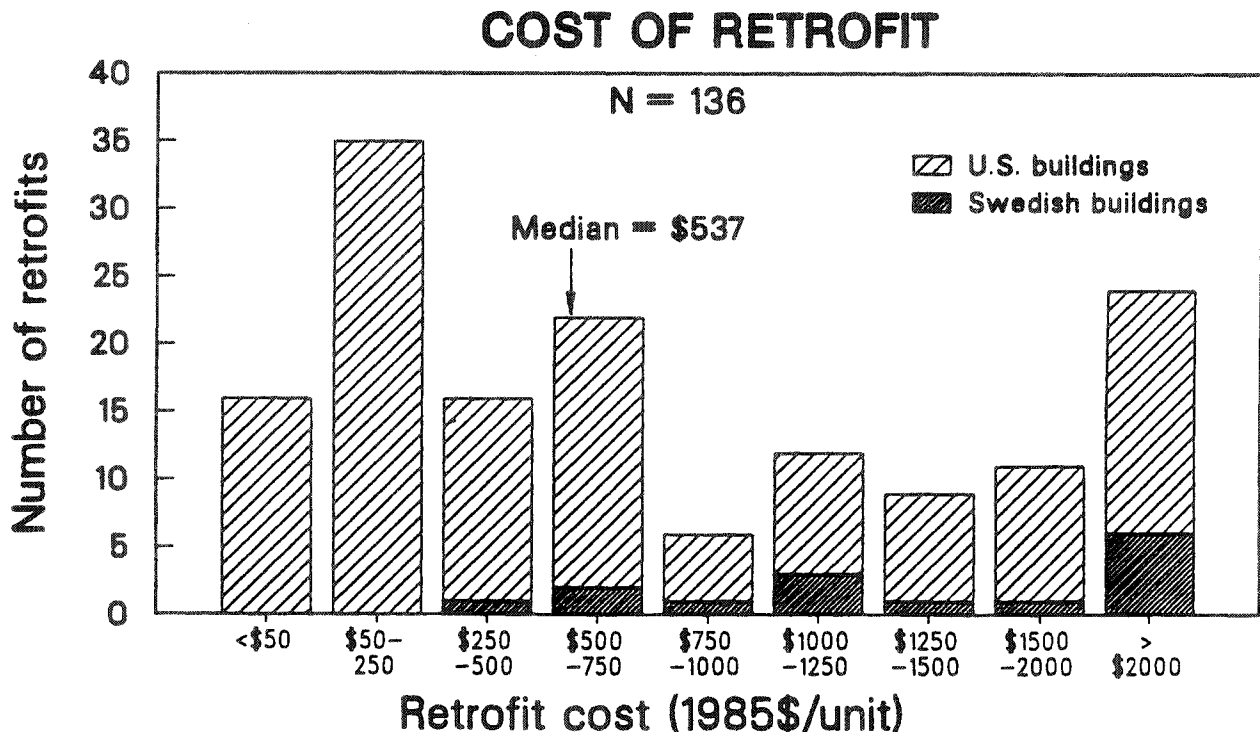


Fig. 2. Distribution of retrofit costs for buildings in the data base.

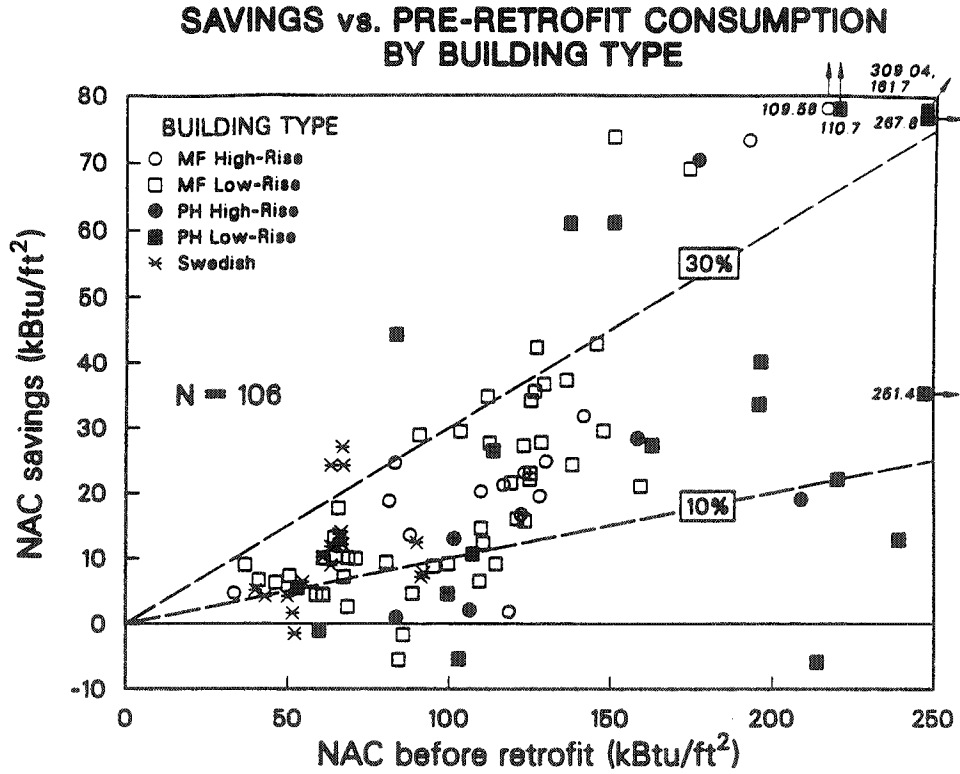


Fig. 3. Plot of energy savings as a function of pre-retrofit energy use, grouped by building type (low-rise versus high-rise) with public housing and Swedish buildings identified separately. Electricity use is expressed in terms of site energy, 3,412 Btu per kWh.

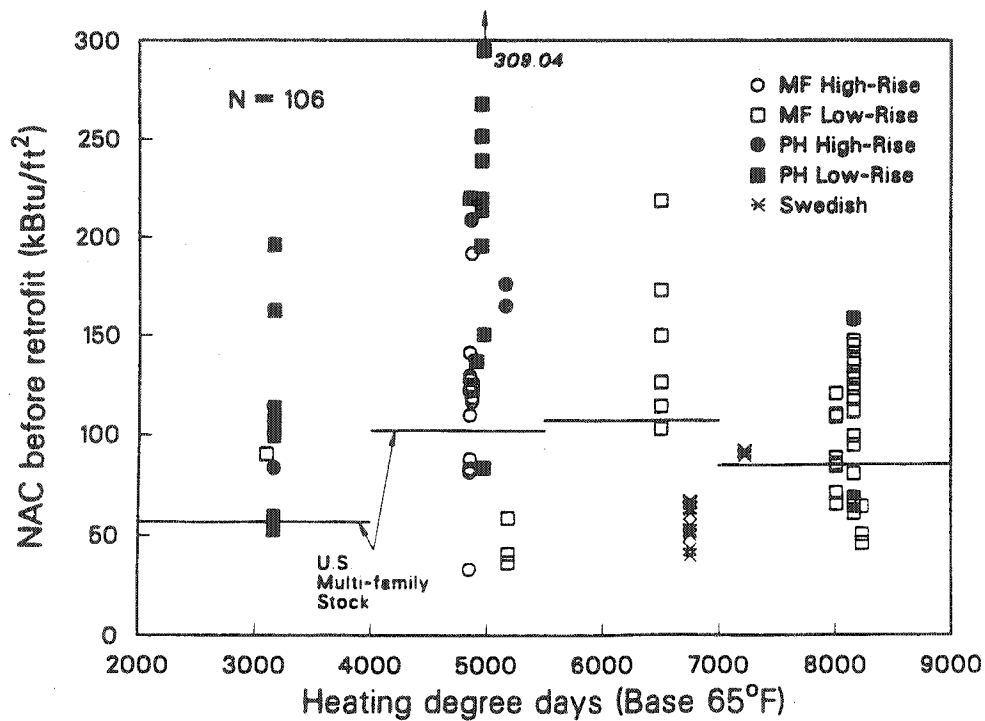


Fig. 4. Energy use before retrofit (NAC) is plotted against heating degree-days (base 65°F) for each retrofit project.

## ENERGY SAVINGS vs. COST BY STRATEGY

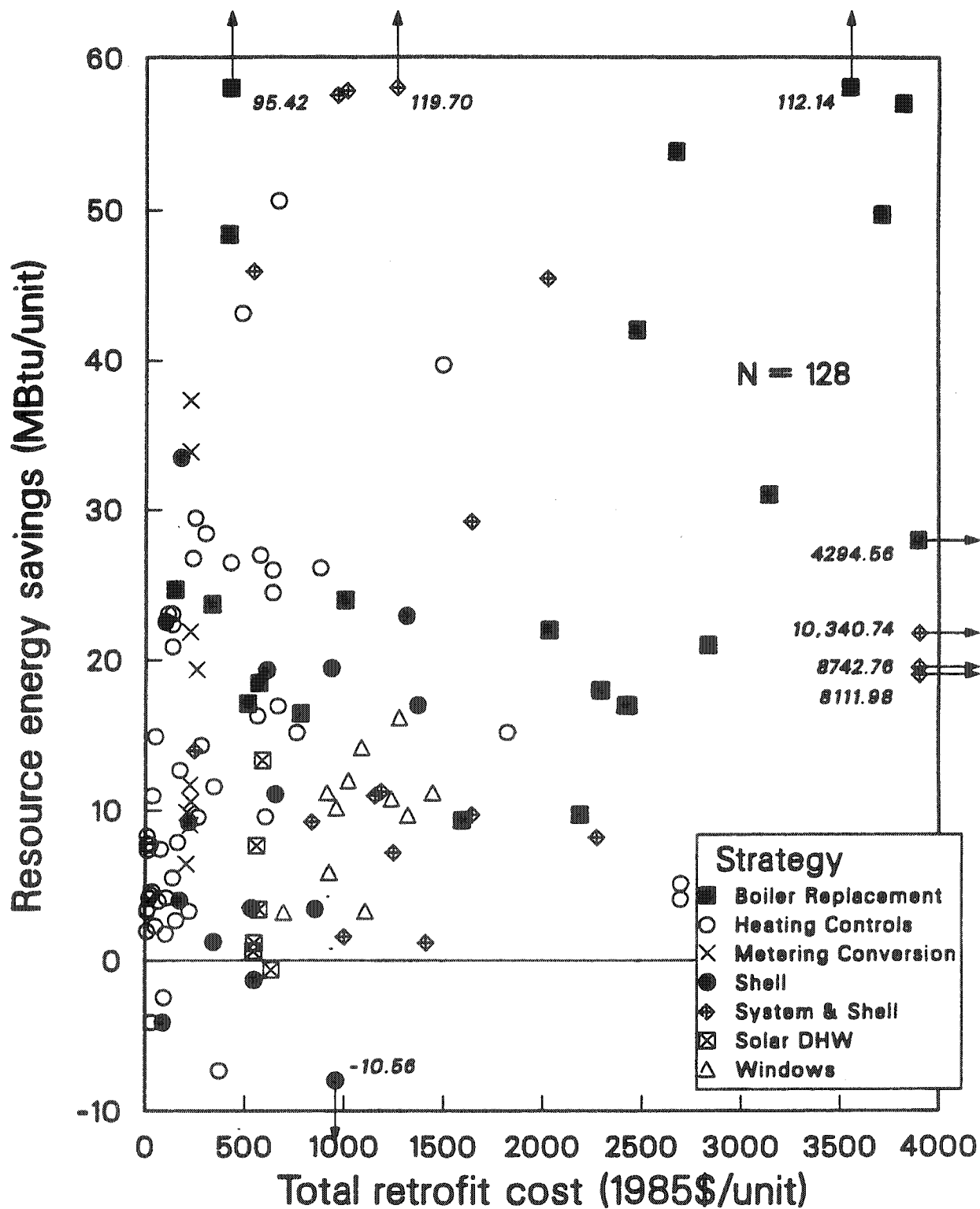


Fig. 5. Annual resource energy savings are compared to the total cost of the retrofit investment in 128 multi-family buildings. In most cases, the savings include changes in consumption for all end uses of the space heat fuel (i.e., domestic hot water, cooking). Electricity is measured in resource units of 11,500 Btu per kWh.

## SAVINGS AND COSTS OF MULTIFAMILY RETROFIT STRATEGIES

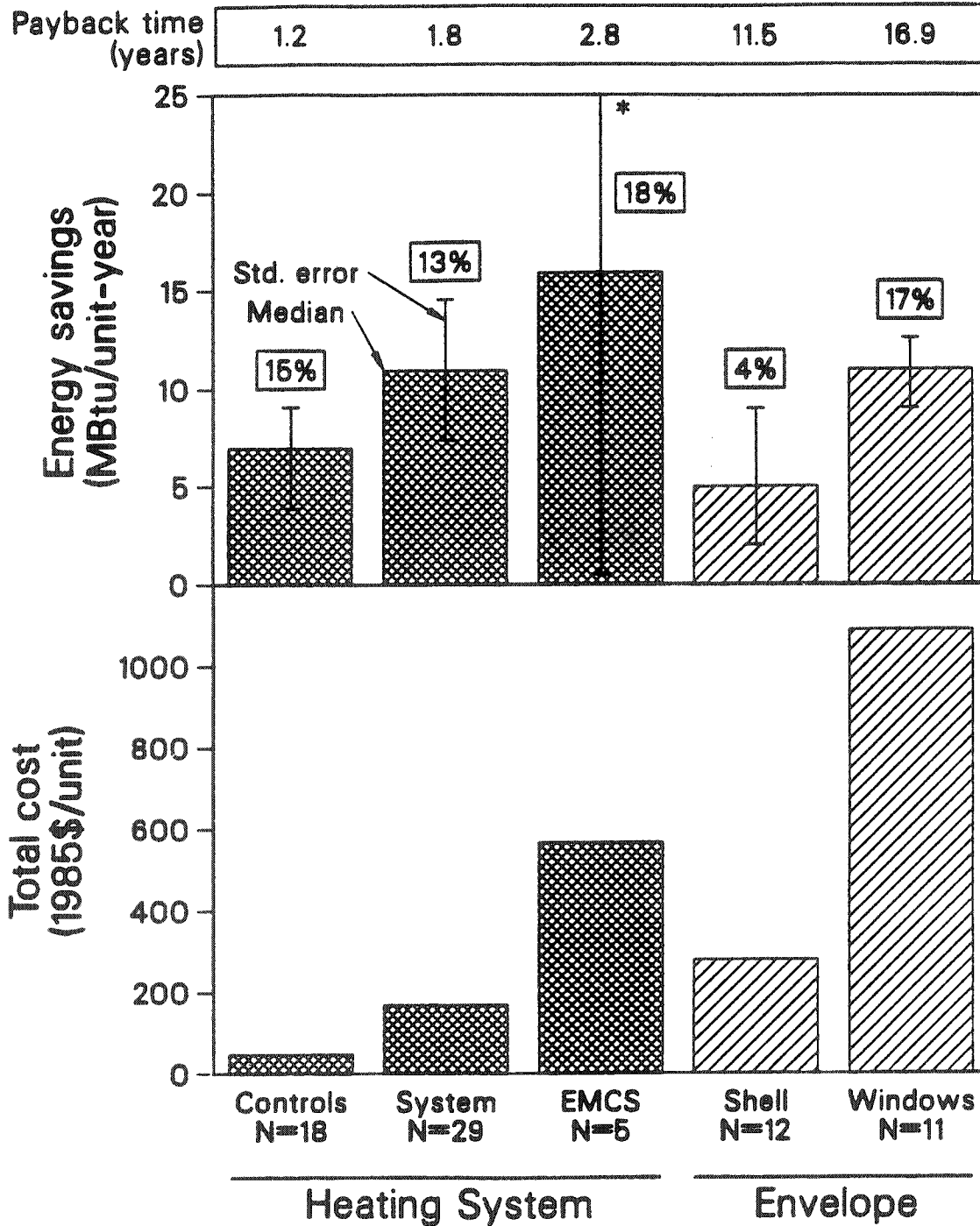


Fig. 6. Energy savings and costs of heating system and envelope retrofits in multi-family buildings. "System" refers to groups of measures that affect the heating or hot water systems. "EMCS" are energy management control systems. "Shell" includes combinations of retrofits which reduce heat loss through the building shell.

\* The upper bound for one standard error is at 33 MBtu/unit-year.