AN UPDATED COMPILATION OF MEASURED ENERGY SAVINGS IN RETROFITTED MULTIFAMILY BUILDINGS

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ABSTRACT

In this study, we compile and analyze measured data on 191 retrofit projects in U.S. multifamily buildings, representing over 25,000 dwelling units, that are included in the Buildings Energy Use Compilation and Analysis (BECA) residential data base. We have added sixty buildings, including forty buildings that heat with electricity, since our initial compilation which was presented at the 1986 Summer Study. We focus on three topics: 1) a more detailed examination of retrofit costs, including costs for individual measures, 2) an analysis of factors that influence energy savings in fuel- and electric-heat buildings, and 3) an estimation of the savings potential and cost associated with retrofitting the U.S. multifamily stock using results based on measured data.

We found that various HVAC system retrofits (heating controls, equipment replacement, and altered operation and maintenance practices) and domestic hot water system alterations were the most popular conservation strategies in fuel-heat buildings. Shell measures (insulation, weatherization, and window modification or replacement) and low-cost DHW retrofits were typically installed in our sample of buildings that heat with electricity. The median retrofit costs for the entire sample of buildings was about $600/unit; 35% of the building owners invested less than $250/unit. Median costs were much lower in fuel-heat buildings ($370/unit) compared to electric-heat buildings ($1,600/unit). Our analysis suggests that the choice (i.e., system versus shell) and intensity of retrofit are the key factors that account for this large cost difference. Heating system retrofits typically cost much less than shell retrofits ($150 versus $1,350/unit). Costs for some individual retrofits, notably steam balancing and steam to hot water conversions, varied by a great deal among different projects (up to a factor of 7).

Median energy savings were 1,450 kWh/unit (5 MBtu/unit in site energy) in electric-heat buildings and 14 MBtu/unit in fuel-heat buildings, about 14-16 percent of pre-retrofit consumption in each case. Energy savings were between 10 and 30% of pre-retrofit energy use in 60% of the buildings. Median payback time in fuel-heat buildings was six years; paybacks were typically 20-25 years in electric-heat buildings where the emphasis was on costlier shell improvements. The regression models for fuel- and electric-heat buildings explained about 60% of the observed variation in energy savings. Pre-retrofit consumption, retrofit costs, type of retrofit, and energy prices were significant determinants of savings. Extrapolating these documented retrofits to the U.S. multifamily stock, we found that between 0.2 and 0.5 quads per year could be saved, depending on the level of effort invested. Based on actual costs recorded for buildings in our data base, we estimate that retrofitting the entire multifamily stock with the "typical" retrofit package would cost about $7.5 - $11 billion; the "intensive" retrofits would cost $27 - $32 billion. Such an investment would represent energy savings of 10-22%, which is well below the "technical potential" for conservation in this sector of 40%, as estimated by the Office of Technology Assessment.

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INTRODUCTION

At the 1986 ACEEE Summer Study, we presented our initial compilation of measured data on the energy savings achieved from retrofitting existing multifamily buildings. Since then, we have added 60 buildings to the data base, and extended our analysis to include the performance of retrofits in electric-heat buildings. This study focuses on three new topics: 1) a more detailed examination of retrofit costs in multifamily buildings, including costs for individual measures, 2) analysis of factors that influence energy savings in fuel- and electric-heat buildings (energy intensity prior to retrofit, level of investment, and choice of measures), and 3) estimation of the savings potential and cost associated with retrofitting the entire U.S. multifamily stock.

DATA SOURCES AND ANALYSIS METHODS

The BECA multifamily data base currently includes 191 U.S. retrofit projects, representing more than 25,000 apartment units.† Our data collection effort focused on buildings with five or more units, since single-family retrofit techniques are often more applicable to smaller multifamily buildings. We obtained information on retrofit projects from several sources, including city energy offices [70], public housing authorities [38], research institutions and national laboratories [17], non-profit and for-profit energy service companies [36], and utilities [39]. (Numbers in brackets represent the number of data points obtained from each source.) In most cases, each data point represents one building, except for public housing projects, which often have a number of buildings on one utility master meter.

The Princeton Scorekeeping Method (PRISM) was used to analyze whole-building energy consumption data before and after retrofit for most of the buildings (Fels, 1986). For fuel-heat buildings, the end uses included in the normalized annual energy consumption (NAC) were space heat, hot water, and, in some cases, cooking; most of the electric-heat buildings were "all-electric" so the NAC included all household end uses. Where only seasonal or annual energy data were available, estimated space heat energy use was weather-normalized using the ratio of that year's heating degree-days (base 65°F) to HDD for an average year. For easy comparison, energy use at each project is expressed per dwelling unit. We had information on vacancy rates for 34 buildings and, in these cases, pre- and post-retrofit energy use was normalized by the number of occupied units. A detailed discussion of data quality and analysis methods, as well as data tables and project descriptions, can be found in Goldman, et al. (1988).

BUILDING AND RETROFIT CHARACTERISTICS

Structural and Demographic Characteristics

The 191 multifamily buildings in this study are typically small- to medium-size buildings with at least five units. Structural and demographic characteristics of buildings in the data base are compared with values for the U.S. stock in Table I. Stock values are for households living in buildings with five or more units. Buildings in this study are similar to the national multifamily stock in terms of apartment size (800 ft^2 versus 780 ft^2), ownership patterns (90% renters), and the split between low- and high-rise buildings. However, compared to the U.S. multifamily stock, buildings in our sample tend to be older, heat less often with electricity, are more likely to have central heating, are located in more severe heating climates, and are more likely to be in a public housing project (20% versus 11% of the building stock with five or more units) (EIA, 1986).

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

Table I. Building and demographic characteristics.

	Fuel Heat (private)	Fuel Heat (PHA)	Elec. Heat	*% of Total Projects*[a]	*% of MF Stock (RECS)*[b]
• Building Type:					
High-Rise	16	19	2	*19*	*14*
Low-Rise[c]	92	18	40	*78*	*79*
• Dwelling Units per Building:					
< 10	21	7	22	*26*	*33*
10-25	48	6	16	*37*	*34*
25-50	29	9	2	*21*	*9*
50-100	5	8	--	*7*	*6*
100-150	5	6	1	*6*	*4*
150-200	1	2	--	*2*	*1*
> 200	--	--	1	*1*	*3*
• Size of Dwelling Units:					
< 500 ft^2/unit	4	1	3	*4*	*15*
500-750 ft^2/unit	38	10	15	*33*	*37*
750-1000 ft^2/unit	30	24	20	*39*	*28*
1000-1250 ft^2/unit	17	2	3	*11*	*10*
1250-1500 ft^2/unit	3	1	1	*3*	*5*
1500-1750 ft^2/unit	5	--	--	*3*	*2*
≥ 1750 ft^2/unit	2	--	--	*1*	*3*
• Year Built:					
before 1940	56	1	7	*34*	*22*
1940-1960	7	24	5	*19*	*11*
1960-1970	22	7	10	*20*	*19*
1970-1980	13	5	17	*18*	*39*
1980 or after	--	--	2	*1*	*9*

	Fuel Heat (private)	Fuel Heat (PHA)	Elec. Heat	*% of Total Projects*	*% of MF Stock (RECS)*
• Space Heat Fuel:					
Natural Gas	90	16	--	*55*	*52*
Oil	17	19	--	*19*	*17*
Electricity	--	--	42	*22*	*31*
Mixed Fuel[d]	--	2	--	*1*	--
Unknown	4	1	--	*3*	--
• Heating System Type:					
Central	103	35	--	*72*	*47*
Individual Unit	--	3	42	*24*	*52*
• Metering:					
Master-Metered	111	38	2	*79*	--
Individ.-Metered	--	--	40	*21*	--
• Climate Zone:[e]					
1 (> 7000 HDD)	64	1	--	*34*	*14*
2 (5500-7000 HDD)	20	--	1	*11*	*24*
3 (4000-5500 HDD)	26	26	41	*49*	*22*
4 (<4000 HDD)	1	11	--	*6*	*40*
• Occupancy:					
Family	8	28	1	*19*	--
Senior	--	8	2	*5*	--
Adults Only	24	--	--	*13*	--
Mixed[f]	40	2	3	*24*	--
• Ownership:					
Renter-Occupied	86	38	42	*87*	*88*
Owner-Occupied	17	--	--	*9*	*10*

[a] Total number of projects is 191; information is not available on certain building and demographic characteristics.

[b] Source: Energy Information Administration, Residential Energy Consumption Survey 1984 Public Use Data Tape. Percentages are of multifamily *households* living in buildings with five or more apartments/building. About 11% of these households live in public housing. Percentages do not add to 100 because of missing responses.

[c] Low-Rise = 4 stories or less.

[d] "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.

[e] Climate zones as defined by the Residential Energy Consumption Survey (Energy Information Administration, *Housing Characteristics 1984*, 1986, p. 207).

[f] "Mixed" occupancy projects include a combination of the preceding categories.

Gas is the most common space heat fuel (55%) in our sample, followed by electricity (22%). Almost all fuel-heat buildings have central boilers and master meters, while electric-heat buildings typically have baseboard resistance heating and apartments that are individually metered. With few exceptions, the electric-heat buildings are located in the Pacific Northwest. The fuel-heat buildings span all climate zones, although many of the buildings are located in five urban areas: Minneapolis-St. Paul, New York City-New Jersey, Philadelphia, Chicago, and San Francisco. This clustering reflects areas of the country where utilities or other organizations have developed strong multifamily retrofit programs with well-documented results.

Baseline Energy Consumption

Prior to retrofit, most buildings in this study were inefficient compared to the multifamily stock (Fig. 1). Median annual energy consumption for electric-heat buildings was 10,000 kWh per dwelling unit, while fuel-heat buildings used 86 MBtu/unit, both of which are 15-25 percent higher than median values for the stock.† The higher baseline consumption for electric-heat buildings in our sample can be explained in part by their location in more severe heating climates. However, within each climate zone, most fuel-heat buildings still used more energy before retrofit than the respective stock average. Figure 1 shows much more variation in pre-retrofit energy consumption for fuel-heat buildings than for electric-heat buildings.

Retrofit Measures and Costs

In general, retrofit efforts focused on reducing space heating and domestic hot water (DHW) energy use. However, the choice and frequency of measures installed varied depending on heating equipment and fuel. Heating system measures were the most popular strategies in fuel-heat buildings. Heating controls, such as outdoor resets, high-limit outdoor cutouts, and thermostatic radiator vents, were installed in more than 50% of the fuel-heat buildings, while various heating system equipment retrofits (e.g., vent dampers, new burners) were added to 35% of these buildings. In contrast, retrofit efforts in electric-heat buildings were directed mainly towards reducing losses through the building envelope and improving the efficiency of the DHW system. For example, about 70% of the electric-heat buildings received window retrofits and low-cost measures to reduce hot water energy use (such as insulating the water heater tank and installing low-flow showerheads). Attic and floor insulation were installed in 50% of the electric-heat buildings; in contrast, attic insulation was installed in only 20% of the fuel-heat buildings. The low implementation rates for shell insulation in fuel-heat buildings are the result both of long estimated payback times, compared to many system retrofits, as well as the existence of structural barriers which limit the applicability of certain shell measures (e.g., masonry walls, which make it more costly to install wall insulation).

The median retrofit cost for the entire sample of buildings was about $600/unit; 35% of the building owners invested less than $250/unit. Median costs were much lower in fuel-heat buildings ($370/unit) than in electric-heat buildings ($1,600/unit). Our analysis suggests that the type of retrofit (system versus shell) and program design are primarily responsible for this large cost difference. For example, shell retrofits, which were commonly installed in electric-heat buildings, had a median cost of $1,300/unit compared to system retrofits in fuel-heat buildings which typically cost $150/unit. In addition, many of the fuel-heat buildings were drawn from programs that consciously chose to focus on implementation of a few low-cost measures. In contrast, electric-heat buildings in this study were drawn primarily from utility conservation programs that focused on comprehensive retrofits and subsidized some or all of the installation costs (Sumi and Newcomb, 1986; Yoder and Schoch, 1987). Therefore, retrofits to electric-heat buildings were typically more expensive because the utilities were willing to accept longer payback times than most building owners. For example, Seattle City Light tried such experimental measures as exterior wall insulation in their program, and buildings retrofitted as part of the Hood River Conservation Project received much higher levels of insulation than are commonly installed.

We also compiled information on the cost of individual conservation measures, including total costs and the cost of materials only, based on reported costs for buildings that participated in six different programs (see Table II). The organizations that initiated these programs are located mainly in the Midwest and Pacific Northwest. Installed

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† Stock values were calculated from the Residential Energy Consumption Survey (RECS) (EIA, 1986 and 1987). However, only 18% of the fuel records were usable for multifamily buildings with five or more units. Fuel consumption was largely imputed from single-family and 2-4 unit multifamily buildings. However, no other source of nationwide data exists on multifamily building energy consumption.

costs per building for steam balancing and steam to hot water conversions varied widely (up to a factor of seven). Some of the variation in costs reflects differences in building size (number of apartments), because a portion of the retrofit costs are variable and scale with the number of units (e.g., radiator vents for individual apartments in steam balancing). Costs for most other heating system retrofits were more uniform, varying by a factor of three; the cost of materials typically accounted for about 60% of the total installed cost for heating controls and vent dampers. The cost of floor and attic insulation varied by a factor of three (up to about \$1.00/ft^2), although costs were significantly higher for buildings that participated in the Hood River Conservation Project (\$1.50/ft^2).

Initial retrofit costs for electric-heat buildings were more than three times as high, on average, as annual energy expenses (i.e., the investment index was 3.4).† In contrast, initial retrofit costs were only 50% of annual energy costs in fuel-heat buildings (i.e., investment index = 0.5). Fuel-heat multifamily buildings managed by public housing authorities were more likely to receive capital-intensive retrofits than were privately-owned buildings (investment intensity = 1.7 for public housing versus 0.4 for private buildings). The low investment intensities in privately-owned fuel-heat buildings illustrate the difficulty of convincing building owners to undertake substantial investments in end-use efficiency unless offered incentives or reduced risks (e.g., low-interest loans, rebates, energy service companies that guarantee savings or maximum energy bills after retrofit).

RESULTS

Energy Savings

Median annual energy consumption decreased by 14 MBtu/unit after retrofit in fuel-heat buildings and by 1,450 kWh/unit in electric-heat buildings. The percentage reduction in pre-retrofit usage was comparable in the two groups (16% and 14%, respectively).‡ The percent reduction in space heating use alone is higher than the reduction in total consumption, but difficult to estimate reliably with only utility billing data, even using the PRISM regression model, as the standard error of the temperature-dependent term is usually 10-20%, while that of the NAC is only 3-4%.

The choice of retrofit strategy was an important factor affecting energy savings and cost-effectiveness. We classified each retrofit project by strategy (e.g., window measures, heating controls) and, in some cases, grouped projects into broader categories (heating/hot water system packages, shell packages, and "system and shell" packages). Figure 2 shows median energy savings, costs and payback times for fuel-heat buildings by retrofit category.§ Heating controls and system retrofits were relatively low-cost strategies that typically saved about 7-9 MBtu/unit (11-13%) with short payback times (one to six years). Replacement or conversion of an existing heating system was much more expensive (\$2,100/unit) and typically saved about 17-31 MBtu/unit with a payback time of 10 years. "Shell and system" packages, installed in 25 buildings, represent the most comprehensive retrofit efforts. They saved 26% of pre-retrofit energy use with an initial investment of about \$1,000/unit, resulting in an attractive payback of six years. Window retrofits had the longest payback times, due to high costs (about \$1,400/unit) coupled with energy savings of 12%.

Retrofit economics were generally less favorable in our small sample of electric-heat buildings (Fig. 3). The dominant retrofit strategies, shell and window measures, had payback times between 18 and 23 years. For these retrofits, percentage savings were comparable to the low-cost heating system and control retrofits in fuel-heat buildings; however, since the costs were much higher (\$1,000-1,400/unit), the paybacks were much longer. Figure 3 also shows results of a demonstration project that involved individual metering conversions of large buildings that were constructed with master metering for electricity. Prior to the early 1970s, master metering was popular in New York because of relatively low electricity prices, bulk discount rates offered by the utilities, and lower construction costs compared to installation of individual electric meters (NYSERDA, 1986). Tenants reduced their electricity consumption for lights and appliances by 18% in four apartment complexes after installation of various submetering technologies (e.g., electronic metering using carrier-wave technology for communications).

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† The investment index is defined as the ratio of the first cost of the retrofit to annual pre-retrofit energy expenditures.

‡ Refers to percentage reduction in energy consumption of the space heat fuel, which typically includes other end uses (i.e., hot water, cooking, and, in electric-heat buildings, lighting and other appliances).

§ Payback time, as used in this study, includes changes in operation and maintenance costs.

Table II. Contractor costs for individual measures.

Measure	*Sponsors*[a] *(# Buildings)*	*Installed Cost (1987 $)*	*Materials Only (1987 $)*	*Reasons for Variation*
HEATING & DHW SYSTEM:				
Front-End Boiler	ERC (2)	7700 per bldg.		
Boiler Derating	CNT (7)	450 per bldg.	70 per bldg.	
Steam Balancing	MEO,ERC,CNT (17)	600 - 4700 per bldg.	310 - 2500 per bldg.	boiler tune-up ∝ # bldgs., controls & vents ∝ # apts.[b]
Steam to Hot Water:				
Single Pipe	MEO (4)	25000 - 75000 per bldg.		boiler replacement ∝ # bldgs., distribution system ∝ # apts.
Double Pipe	MEO,ERC (5)	2600 - 19000 per bldg.		some boilers replaced, pipe access varies
Heating Controls:				
Reset & Cutout	MEO (18)	530 - 680 per bldg.		
TRV	NYCHA (4)	43 - 64 each	26 - 38 each	
Night Setback	CNT (4)	150 - 470 per bldg.	94 - 100 per bldg.	∝ # apts.
Vent Dampers:				
Electronic, space heat				
--Standard	ERC (1)	470 per bldg.		vent damper only
--Custom	MEO (4)	920 - 1900 per bldg.	580 - 1200 per bldg.	includes new gas valves, electronic ignition
Thermal, space heat				
--Standard	CNT (4)	210 per bldg.	120 per bldg.	vent damper only
Electronic, DHW				
--Custom	MEO (2)	620 - 1700 per bldg.	420 - 1300 per bldg.	includes new gas valves and controls
Thermal, DHW				
--Standard	ERC (1)	150 per bldg.		vent damper only
Shower Flow Restrictor	CNT (7)	15 each	3 each	
Low-Flow Showerhead	CNT,SCL (12)	28 each	14 each	
SHELL:				
Ceiling Insulation	SCL,ERC,CNT (16) HR (43)	0.39 - 0.93 per ft^2 1.50 per ft^2		added at least R-22, up to R-40 Added R-49
Floor Insulation	SCL (12) HR (28)	0.56 - 1.10 per ft^2 1.40 - 1.50 per ft^2		added at least R-19, up to R-30 added at least R-19, up to R-38
Windows:				
Adding 1 Layer	HR,SCL (32)	6 - 14 per ft^2		low=conversion, high=replacement
Adding 2 Layers	HR (40)	12 per ft^2		replace & convert
Storm Doors	ERC (1)	210 each		
Door Weatherstripping	ERC (1)	46 / door	6 / door	
Door Caulking	SCL (1)	73 / door		

[a] CNT=Center for Neighborhood Technology, ERC=Energy Resource Center, HR=Hood River Conservation Project, MEO=Minneapolis Energy Office, NYCHA=New York City Housing Authority, SCL=Seattle City Light.

[b] "∝" means "proportional to".

Determinants of Energy Savings

We also used multivariate regression analysis to determine which of these characteristics have the most influence on the magnitude of energy savings in our sample of retrofitted multifamily buildings, when the other variables associated with savings are held constant. We used a two-stage process to analyze factors related to energy savings, similar to the method suggested by Hirst (1987). First, we used the PRISM model to weather-normalize the measured first-year energy savings to a year with typical weather. Energy savings at each project were normalized for conditioned floor area and included only first-year savings.†

In stage two, we looked at the cross-sectional variation in savings among projects as a function of structure, retrofit, and demographics. Independent variables included in the original regression analysis are listed in Table III.

Table III. Initial variables used in regression models.

retrofit characteristics	type of measure[a,b] cost/ft^2 (1987 $) year of installation
building structural characteristics	high- or low-rise[a] number of floors dwelling units per building year built conditioned area masonry or frame construction[a]
existing equipment and its operation	central or individual heating system[a] oil/gas/electric space heat fuel[a] steam/hydronic/resistance heat distribution[a]
occupant/ownership characteristics	renters or owners[a] public or private housing[a]
climate severity	long-term average heating degree-days base 65°F
pre-retrofit use	annual energy consumption (kBtu/ft^2)[c]
energy prices	1987 $/site MBtu

[a] These are dummy variables, indicating the presence or absence of a condition. All other variables are continuous.

[b] Types of measures include: BOILER (replacement of space heat boiler), BOILER & WINDOWS (replacement of space heat boiler and windows), DISTRIBUTION CONV. (conversion of space heat system from steam to hot water distribution), ENERGY MANAGEMENT (computerized energy management system), HEATING CONTROLS (new controls for space heat system), METER CHANGE (conversion of fuel or electricity use from master- to individual-metering), SHELL (package of retrofits to the building envelope), SHELL & SYSTEM (package including envelope and heating system retrofits), SOLAR DHW (solar heating panels for producing domestic hot water), SYSTEM (package of retrofits to heating and/or DHW system). Note that these retrofit categories are mutually exclusive; that is, the conservation measure done in each building are assigned to *one* of these groups. For example, if both attic insulation and heating controls are installed in a particular building, the retrofit type would be "shell and system".

[c] Total consumption of the space heat fuel. For fuel-heat buildings, end uses included are space heat, domestic hot water, and, in some cases, cooking. Lighting and appliances are also included in electric-heat buildings; consumption is converted to site MBtu using 3,413 Btu=1 kWh.

Most of the independent variables in the regression equation were "dummy variables", indicating the presence or

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† We used savings/ft^2 as the dependent variable, rather than savings/dwelling unit, because the former was distributed more normally for our projects.

absence of a condition. For example, the eleven types of retrofit measures were represented by ten dummy variables (which we'll refer to as "alternates"), that took on values of zero or one to show the presence or absence of a particular retrofit. The eleventh case (window retrofits in our models) is represented when the ten dummy variables all equal zero; therefore, the coefficients of the retrofit variables are relative to this "reference case".

Using these characteristics, we developed two regression equations each for fuel- and electric-heat buildings, with and without pre-retrofit consumption as an independent variable. The final analysis included 173 retrofit projects (137 fuel-heat projects and 36 electric-heat buildings). The final regression models include all variables (and their alternates, if any) that were significant at the 10% level.† Statistically insignificant and highly correlated variables (those with a correlation coefficient greater than 0.7) were eliminated based on preliminary regression analyses.

The final regression models that included pre-retrofit energy use explained 57 to 61% of the variation in energy savings in fuel- and electric-heat buildings respectively, as measured by the adjusted R^2 (see Table IV). In fuel-heat buildings, *pre-retrofit use* alone accounted for 37% of the variation in savings. Pre-retrofit energy use in electric-heat buildings, although significant, was much less influential whereas retrofit cost alone accounted for almost 40% of the variation in savings. The coefficients of both pre-retrofit use and retrofit cost are positive, indicating that larger energy savings are obtained in buildings with higher pre-retrofit use or increased levels of investment in retrofits.

Choice of retrofit strategy is another key determinant of energy savings. In the fuel-heat buildings, savings from "shell and system" and boiler retrofits were up to 28-33 kBtu/ft^2 higher than savings from the least effective retrofit strategies (i.e., shell retrofits). Installation of computerized energy management systems and conversions of steam heat distribution systems to hot water produced savings of 18-20 kBtu/ft^2 more than the shell retrofits. Choice of retrofit strategy was also important in explaining the variation in savings among electric-heat buildings, although only three main types of strategies were implemented. For example, shell and combined "shell and system" retrofit packages were both statistically significant variables. Relative to savings from window retrofits (our "reference case"), energy savings were about three and eight kBtu/ft^2 lower for shell and combined "shell and system" retrofits, respectively.

Even though choice of retrofit strategy was an important determinant of savings, the way in which the model was specified, and limitations of our data set led to some anomalous results. For example, "boiler and windows" retrofits saved less energy than "boiler" retrofits alone; these parameter estimates are physically counterintuitive. Because the retrofitted buildings classified under "boiler" are not a subset of, but rather a separate group from, those classified under "boiler and windows", building-specific differences which are not directly accounted for by our model could influence energy savings, particularly in a small sample of buildings. These differences include the degree of over-sizing of the original boiler. These inconsistencies lead us to conclude that it would be imprudent to extend the specific results of these models to retrofit experience in general. However, based on this analysis, we believe that pre-retrofit use, retrofit cost, and choice of strategy are key determinants of energy savings, although the relative magnitude of savings from different conservation measures are valid for this group of buildings only.

We also developed regression models for fuel- and electric-heat buildings in which pre-retrofit consumption was excluded as an explanatory variable. We wanted to explore whether structural variables might be more important in this situation. The regression models that did not include pre-retrofit energy use as an explanatory variable accounted for 5-10% less of the variation in savings than the models that included this variable (adjusted R^2 of 0.46 and 0.56 for fuel- and electric-heat buildings, respectively). Even after we excluded pre-retrofit energy consumption, variables related to building structural characteristics were not statistically significant at the 90% confidence level in explaining variation in savings. The magnitude and sign of parameter estimates were quite similar in comparing both models for the electric-heat buildings. For the fuel-heat buildings, retrofit cost became statistically significant, while choice of retrofit strategy explained the most variation in savings. For example, "shell and system" retrofits alone explained 27% of the variation in savings.

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† Non-significant alternates of dummy variables were also kept in the equation. Since coefficients for dummy variables are always with respect to the "reference case", simply eliminating the non-significant alternates would change the value of the significant parameters. In the case of retrofit type, eliminating the non-significant retrofits would be equivalent to assuming that these buildings all received window retrofits.

Table IV. Regression model results for fuel- and electric-heat multifamily buildings.[a]

Explanatory Variable[b]	Fuel-Heat		Electric-Heat	
	w/ pre	w/o pre	w/ pre	w/o pre
PRE-RETRO. USE (kBtu/ft^2)	--	--	0.1 *	--
LN (PRE-RETRO. USE) (kBtu/ft^2)	23.7 *	--	--	--
RETRO. COST (1987 \$/ft^2)	--	5.4 *	2.9 *	2.9 *
Retrofits[c]:				
BOILER	28.0 **	38.6 **	--	--
BOILER & WINDOWS	9.1	4.4	--	--
DISTRIBUTION CONV.	13.6 *	16.0 *	--	--
ENERGY MANAGEMENT	16.2 *	28.1 **	--	--
HEATING CONTROLS	2.9	6.4	--	--
METER CHANGE	7.1	14.3 *	--	--
SHELL	-4.1	6.9	-2.6 *	-2.1
SHELL & SYSTEM	32.6 **	40.9 **	-8.4 **	-7.6 **
SOLAR DHW	2.0	-2.0	--	--
SYSTEM	5.4	11.5	--	--
ENERGY PRICE (1987 \$/MBtu)	--	--	1.4 **	1.6 **
Constant	-98.7 *	4.3	-9.4 **	-5.5 *
Number of Cases	137	137	36	36
Adjusted R^2	0.57	0.46	0.61	0.56
R^2	0.61	0.51	0.66	0.61

* Significant at 90% level.

** Significant at 95% level.

-- Not included in the equation.

[a] Model coefficients are unstandardized. Separate models were developed for fuel- and electric heat buildings including and excluding pre-retrofit consumption as an explanatory variable. Residuals were examined for normality and heteroscedascity; where appropriate, logarithmic transformations were made in the final models. Note that residuals in the final fuel-heat model were still somewhat heteroscedastic.

[b] Since the dependent variable is measured in kBtu/ft^2, the coefficients of these variables reflect a change in savings in kBtu/ft^2 for each one-unit change in the explanatory variable. Electricity use is converted to kBtu using 3,413 Btu=1 kWh.

[c] If not any of these retrofits, then window replacement or modification.

Estimation of Stockwide Savings Potential

We estimated the nationwide energy saving potential using the measured results from multifamily retrofits (Meier, et al., 1988). Installed retrofits were grouped into "typical" and "intensive" packages, and median savings were calculated for each major building and heating system type. As we defined it, a "typical" retrofit represents what a building owner would be willing to invest under current market conditions. Owners generally will not invest in "intensive" retrofit packages without incentives from government or utilities or some sharing of risks. Typical retrofits for fuel-heat buildings include heating and domestic hot water system retrofits; attic insulation, window treatments, and system measures were included in the intensive package. Typical retrofits for electric-heat buildings include insulation and window treatments, while higher levels of insulation and window and door treatments were part of the intensive package for these buildings. We made separate estimates of stockwide savings potential for four major market segments, based on the kinds of retrofits applicable to each building and system type: 1) fuel-heat buildings with central steam distribution systems, 2) fuel-heat buildings with central hot water distribution systems, 3) fuel-heat buildings with individual apartment space heaters, and 4) electric resistance-heat buildings.

Median fuel savings for typical retrofit efforts in fuel-heat buildings with central heating systems (groups 1 and 2) ranged from 6 to 18 kBtu/ft^2 (13-15% of pre-retrofit fuel usage). More intensive retrofit efforts in these two groups yielded savings of 45-50 kBtu/ft^2 (35% of pre-retrofit fuel consumption). Savings from typical retrofits were about 10% for fuel-heat buildings with individual unit heating, although our sample is relatively small. Because the BECA data base did not contain any examples of intensive retrofits for fuel-heat building with individual unit heating, we assumed the same percentage savings from intensive retrofits for this segment as for fuel-heat buildings with central heating. This assumption is valid because the same types of retrofits are included in the "intensive" package for both groups (e.g., attic insulation). Median electricity savings in individually-metered buildings with electric baseboard heating were 10% and 19%, respectively, for typical and intensive retrofits.

The measured savings for each group were extrapolated to the U.S. multifamily stock using information on consumption and building characteristics obtained from the 1984 Residential Energy Consumption Survey (RECS). The savings estimates for buildings with 5+ units are based on *direct* extrapolation, while estimates for 2-4 unit buildings — for which there are no measured data — are *indirect.* In other words, the direct extrapolations are based on buildings with similar characteristics, such as heating system and fuel type, and vintage. Savings for 2-4 unit buildings are based on savings obtained in 5+ unit buildings with similar characteristics. Our analysis took into account both the disproportionately high number of multifamily buildings in the sample located in colder climates and the fact that, even after adjusting for climate differences, these buildings used more energy prior to retrofit than the U.S. multifamily stock as a whole.

We adjusted the "direct" and "indirect" stock savings estimates for the effect of differing climatic location between BECA buildings and the stock, using long-term average HDD. Because the BECA buildings are located in more severe heating climates, this adjustment reduced our estimate of savings in the stock. Next, we adjusted the climate-corrected stock savings for remaining differences in pre-retrofit use. Since BECA buildings have higher pre-retrofit consumption than the stock, this adjustment also reduced the stock savings estimates.

After adjusting for differences in climate and initial pre-retrofit consumption, we found that typical retrofits of U.S. multifamily buildings could save about 0.2 quads per year (in resource energy), and intensive retrofits could save about 0.5 quads per year (Fig. 4). (Electricity is converted at 11,500 Btu = 1 kWh.) These results suggest that current energy consumption in the multifamily sector could be reduced by 9-22% based on documented results from existing conservation programs. Based on actual costs recorded for buildings in the data base, we estimate that retrofitting the entire multifamily stock with "typical" retrofit packages would cost about $7.5 - $11 billion; for the intensive retrofits, $27 - $32 billion. This estimate includes materials and contractor labor costs but does not include conservation program administration costs.

We also performed a relatively simple error analysis in order to estimate the uncertainty in our stock savings values. We assessed the relative magnitude of the error in each key input value at each step of the analysis, which was then used to calculate the standard error of the final estimate of savings potential (see Fig. 4). Our analysis of the uncertainty in the climate- and UEC-adjusted stock savings estimates indicate that the 95% confidence interval for savings from the typical retrofit package was 0.2 ± 0.09 quads/year, and 0.5 ± 0.2 quads/year for the intensive retrofit package. This analysis of quantifiable uncertainty indicates how well determined the results of the extrapolation are, given that our assumptions about how to extrapolate results from the BECA data base to the stock are correct (i.e., assuming we have not omitted any adjustments which would significantly change the results. Variation in savings arising from differences in indoor temperatures or occupant behavior, for example, could have an impact on the results; however, we did not have sufficient data to correct for these influences.) We also performed a less rigorous assessment of the reasonableness of our assumption that savings in 5+ unit buildings apply equally well to 2-4 unit buildings. We compared the measured savings from retrofitted 5+ unit buildings with retrofit performance in single-family houses, as a way of bounding the savings which could be expected from similar retrofits in 2-4 unit buildings; stockwide savings from typical retrofits increased by 0.06 quads if single-family savings are used for the 2-4 unit building stock. However, we based our final results on the more conservative extrapolation of savings from 5+ unit buildings to the 2-4 unit building stock.

The strength of this analysis is that it is based on documented results from existing conservation programs, benchmarked to actual consumption of the existing multifamily stock. Most estimates of the technical potential for retrofit energy savings are based on computer simulations or engineering estimates, rather than empirical data. Other studies of technical potential concluded that consumption can be reduced by about 40% from current levels (OTA, 1982). Despite the limitations of these studies as well as uncertainties in our extrapolation, actual retrofit results at present appear to fall short of the achievable "best practice."

CONCLUSION

Table V summarizes key quantitative results.

Table V. Summary of savings and economic indicators.[a]

	All Buildings	*Fuel Heat (private)*	*Fuel Heat (PHA)*	*Electric Heat*
Number of Buildings	194	113	39	42
Energy Savings[b] (MBtu/unit-year)	9 ± 1	15 ± 2	12 ± 4	5 ± 1
Energy Savings (%)	15 ± 1	16 ± 2	13 ± 2	14 ± 2
Retrofit Cost (1987 $/unit)	600 ± 100	260 ± 80	580 ± 220	1600 ± 240
Invest. Intensity (years)	1.0 ± 0.2	0.4 ± 0.1	1.7 ± 0.3	3.4 ± 0.4
Payback Time[c] (years)	7 ± 1	4 ± 1	10 ± 4	23 ± 7
CCE[b,d] (1987 $/MBtu)	5 ± 1	3 ± 1	8 ± 2	11 ± 3

[a] Values given are medians ± standard errors.

[b] Electricity savings are converted to site MBtu using 3,413 Btu=1 kWh.

[c] Payback times include changes in operation and maintenance costs.

[d] Cost of conserved energy assumes a real discount rate of seven percent and retrofit lifetimes based on field experience with specific measures; it also includes changes in operation and maintenance costs.

Energy consumption after retrofit typically decreased by 12-15 MBtu/unit in fuel-heat buildings, and by about 1,450 kWh/unit in electric-heat buildings. Energy savings were between 10 and 30% of pre-retrofit energy use in 60% of the buildings. We analyzed factors that contribute to the large variation in energy savings and found that differences in pre-retrofit usage, size of investment, and choice of retrofit strategy were particularly influential. Regression models for fuel- and electric-heat buildings explained about 60% of the observed variation in energy savings.

On a per unit basis, retrofit costs were much lower in fuel-heat buildings compared to electric-heat buildings ($370/unit versus $1,600/unit). Key factors that account for these large cost differences include type of retrofit (e.g., system versus shell), program design (e.g, some programs installed a few, relatively low-cost measures, while others emphasized comprehensive retrofits), and, to a lesser extent, economies of scale related to building size. Our results reinforce the view that private multifamily building owners seldom make substantial investments in conservation; median retrofit costs for fuel-heat buildings were only 50% of annual energy costs.

The economics of retrofitting fuel-heat buildings with central systems were quite attractive (e.g., median payback of three years for privately-owned buildings). This was particularly true when conservation efforts focused on heating/hot water system efficiency improvements. Fuel savings of 26% and payback times under six years were achieved in older, fuel-heat buildings that installed a combined package of "system and shell" retrofits. In electric-heat buildings, payback times were often longer than 20 years. In electric-heat buildings, our results suggest that it is not cost-effective to spend more than $2,000/unit, based on savings from the most commonly chosen retrofits. Program economics could be improved by limiting costs, targeting high users, and emphasizing less expensive retrofits, such as lighting and domestic hot water measures.

Extrapolating these documented retrofit results to the U.S. multifamily stock, we found that between 0.2 and 0.5 quads per year could be saved. This estimate, representing 10-22% savings from retrofits, is well below the "technical potential" for conservation of 40%, as estimated by the Office of Technology Assessment.

We believe that compiling and publishing measured data on the performance and cost-effectiveness of retrofit measures and operating strategies is one tool that can help multifamily building owners and tenants make better informed choices about improving the end-use efficiency of their buildings. Topics requiring further research include long-term tracking of retrofit savings and evaluation of load-profile impacts of residential retrofits.

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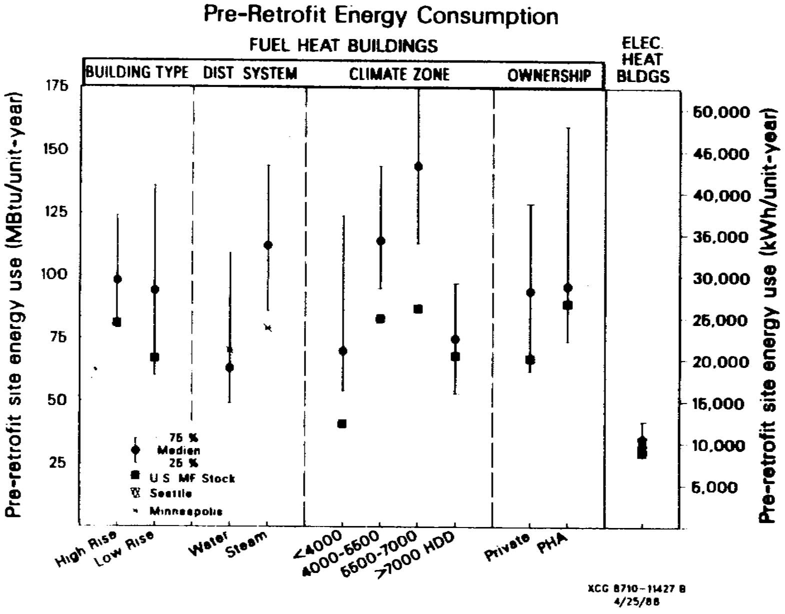

Figure 1. Pre-retrofit energy consumption of multifamily buildings in this study compared to medians for the multifamily stock (with five or more units). Interquartile range in energy consumption is shown for fuel-heat buildings that are privately-owned or managed by public housing authorities (PHA) and for electric-heat buildings, which are mostly located in the Pacific Northwest. Consumption in fuel-heat buildings is also shown segmented by building type, heating distribution system, and climate severity, as measured by annual heating degree-days (base 65°F). Consumption includes total usage of space heat fuel (fuel-heat buildings include space heat, DHW, and some cooking; electric-heat buildings also include lights and appliances).

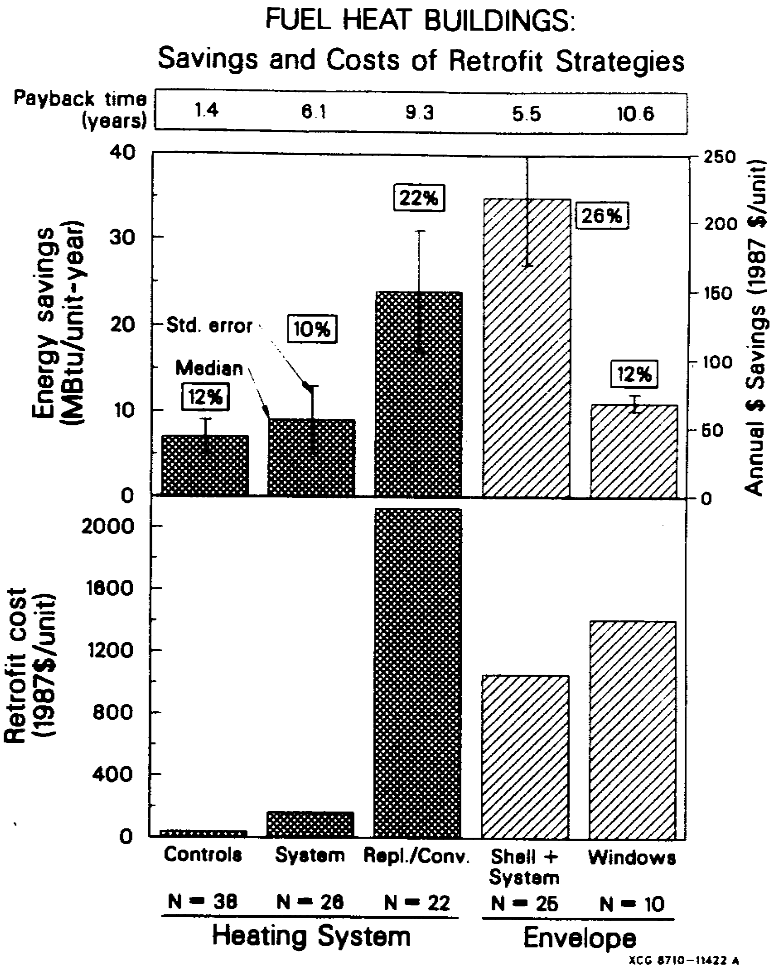

Figure 2. Energy savings, retrofit cost, and payback time of various retrofit strategies in fuel-heat multifamily buildings. *System* retrofits are groups of measures that affect the heating or hot water systems. *Repl./Conv.* include boiler replacements or conversions from steam to hot water distribution. *Shell+System* includes heating/hot water system measures as well as insulation or window retrofits. "N" is the number of projects in each category. The dollar value of fuel savings was calculated using the median gas/oil price (in 1987 $) from the sample of fuel-heat buildings ($6.25/MBtu). Payback time includes changes in operation and maintenance costs.

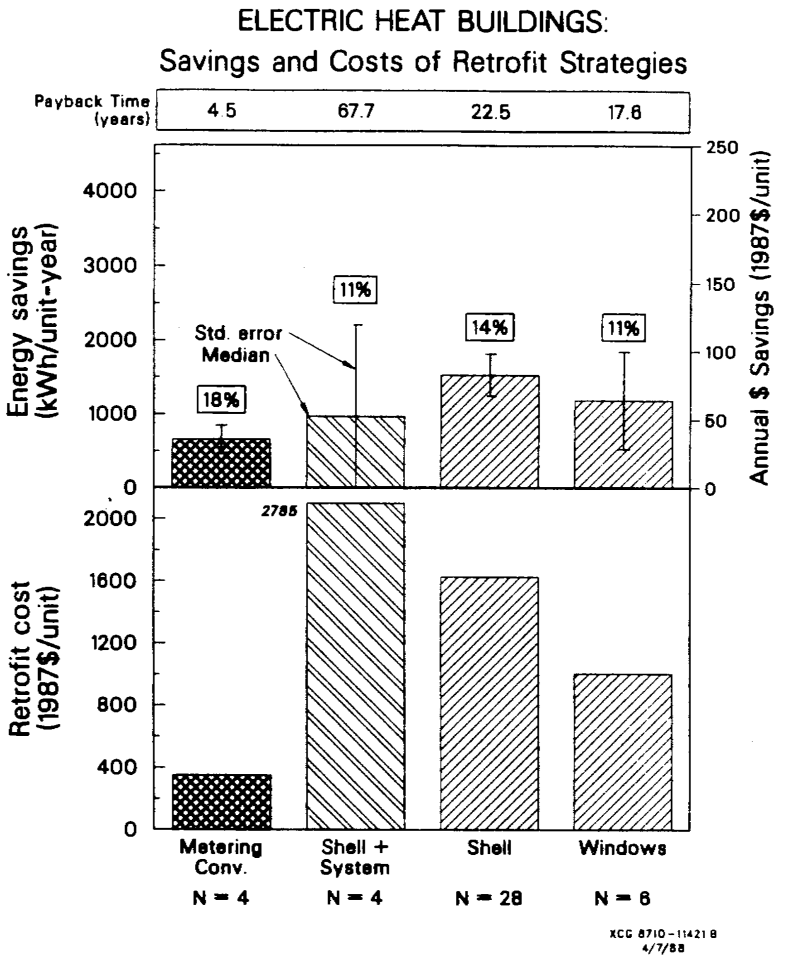

Figure 3. Electricity savings, retrofit cost, and payback time of various retrofit strategies in electric-heat multifamily buildings. The dollar value of electricity savings was calculated using the median electricity price (in 1987 $) from the sample of electric-heat buildings ($0.054/kWh). Payback time includes changes in operation and maintenance costs.

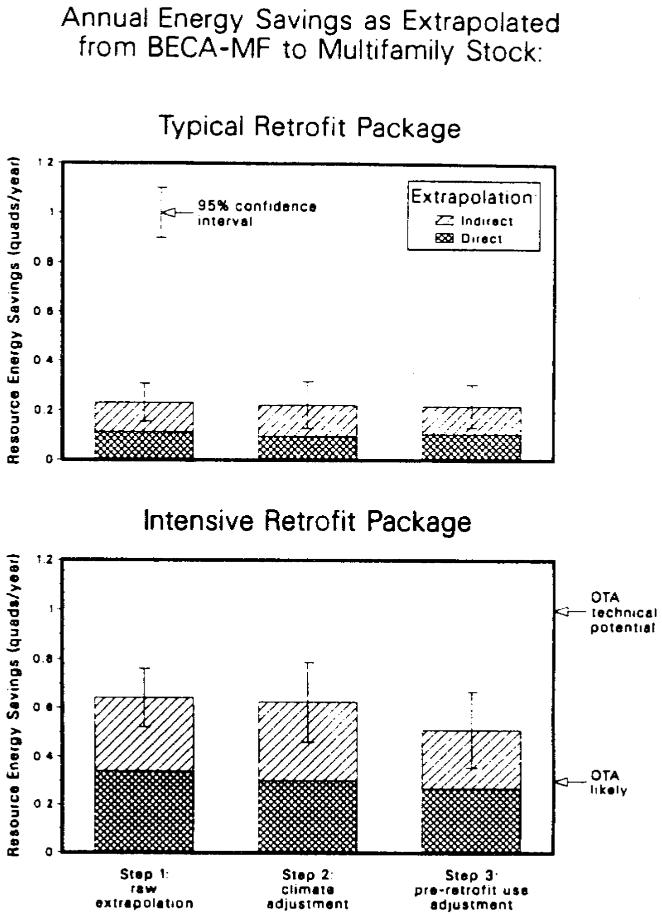

Figure 4. Raw and adjusted nationwide estimates of savings potential are shown for "typical" and "intensive" retrofit packages. "Direct" extrapolation refers to the savings potential for 5+ unit buildings (13.5 million households); savings for 2-4 unit buildings are shown as "indirect" extrapolation (10.0 million households). Estimated technical and likely conservation potential are shown for comparison (OTA, 1982).