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Volume I

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RETROFIT EXPERIENCE IN U.S. MULTIFAMILY BUILDINGS: ENERGY SAVINGS, COSTS, AND ECONOMICS†

Volume I

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INTRODUCTION

Until recently, government- or utility-sponsored programs and research on U.S. residential energy efficiency have focused on single-family homes; multifamily apartment buildings have received much less attention.[1-2] Multifamily buildings represent a significant fraction of all U.S. housing units (about 27%) and consume 2.8 quads per year of primary energy.† Multifamily households spend $20 billion per year, directly or indirectly (i.e., paid as part of rent), for energy.[3] The technical potential for saving energy in these households is quite large; primary energy use could be reduced by one quad, or 40% of projected national consumption in the year 2000.[4] However, likely savings are estimated to be only 13% of projected primary energy consumption, because of various institutional, financial, and technical barriers.‡ These barriers include: 1) unwillingness on the part of building owners to invest in costly measures without guaranteed savings, 2) problems arising from the split in economic interest between landlords and tenants, 3) difficulty in obtaining financing for retrofits, and 4) conflicting information on the performance and costs of retrofits.

Our work addresses this last barrier by compiling and analyzing measured data on the costs of conservation measures and practices in multifamily buildings and on the energy savings they produce.§ We discuss factors that influence energy savings — energy intensity prior to retrofit, magnitude of investment in retrofits, and choice of measures — and identify retrofit strategies that are cost-effective for specific building and heating system types. We also report on the persistence of energy savings over time and compare predicted versus measured energy savings in a subset of the buildings. Finally, we take information on measured savings, for various levels of investment and for each major building type, and use it to estimate the savings potential and costs associated with retrofitting the entire U.S. multifamily stock.

DATA SOURCES AND ANALYSIS

The BECA multifamily data base currently includes 191 U.S. retrofit projects, representing more than 25,000 apartment units (see Appendix A for summary data tables and Appendix B for descriptions of each retrofit project).* Our data collection effort focused on buildings with five

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† The multifamily sector, as defined here, consists of residential buildings with two or more units. One quad equals 10^{15} Btu.

‡ OTA [ref. 4] defined the *technical savings potential* as those retrofits which would be cost-effective over a 20-year lifetime, assuming no real increase in energy prices and a three percent real return on investment (i.e., retrofits with a simple payback time of 15 years). OTA's estimate of *likely savings* is based on retrofits that building owners are likely to invest in given current conditions of capital availability, retrofit information, and conservation programs. Under these conditions, OTA found that owners have a 2-3 year payback criterion.

§ Results are drawn from the Buildings Energy Use Compilation and Analysis (BECA) residential data base at the Lawrence Berkeley Laboratory. Our compilation efforts in the multifamily sector have focused on larger buildings (five or more units).

*At a few sites, a series of retrofits were installed several years apart, which allowed us to analyze savings separately for each retrofit. The total number of *retrofits* examined is 198.

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].†
The data collected typically included metered energy consumption, installed retrofit measures and costs, the price of space heating fuel during 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 for public housing projects, which often have a number of buildings on one utility master meter.

Analysis of Energy Savings: Weather-normalization, Occupant Effects, and Data Quality

In most cases, we used the Princeton Scorekeeping Method (PRISM) to analyze whole-building energy consumption data before and after retrofit. PRISM estimates a weather-normalized annual energy consumption (NAC) using parameters obtained by regressing either utility bills or meter readings of the space heat fuel against daily average outdoor temperature.[5] The NAC represents consumption that would occur in a year with typical weather conditions. For fuel-heat buildings, the end uses included in the 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. With a few exceptions, retrofit projects in this compilation did not have data from end-use metered heating energy or monitored inside temperatures. With the current level of monitoring, secondary heating equipment use or the effects of internal gains from other energy sources might go undetected, which could affect the reported savings from conservation measures.[6] For easy comparison, energy use at each project is expressed per dwelling unit.

We were not able to use PRISM for 55 projects because of data problems (e.g., an insufficient number of actual meter readings, monthly energy data without billing dates, or aggregated annual energy consumption data). In these cases, we corrected for the varying severity of winter in different years by scaling annual estimated space-heat energy consumption by the ratio of normal-year to actual-year heating degree-days (base 65°F). Annual baseload energy use was calculated by scaling estimated summer fuel use (typically provided by building owners) to a full year.

In multifamily buildings, tenant turnover is often high and occupancy rates vary greatly over time.‡ Our analysis does not account for changes in energy use resulting from differences in the behavior of new occupants who may have moved into a building after a retrofit. Occupant effects and vacancies play a particularly critical role in smaller multifamily buildings (<15 units), because unusual consumption patterns in one or two units can significantly bias total building consumption (especially if an apartment is vacant for several months). When information is available, we normalize energy use by the number of occupied units before and after

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

‡ Forty-two percent of U.S. renters remain in their residences for one year or less [Ref. 1]. Evaluations of retrofit programs directed at single-family homes generally exclude homes in which occupancy has changed; this approach is not feasible in master-metered buildings.

retrofit, although this is at best a crude proxy to account for the impacts on energy use of the number of occupants/dwelling unit and the amount of conditioned space.† For example, our method assumes that vacant units are unheated; this may not be true.

Retrofit Costs and Economic Indicators

Retrofit costs reported in this study reflect direct costs to the building owner of contractor-installed measures. We adjusted actual retrofit costs to costs in 1987 dollars using the GNP Implicit Price Deflators. We then calculated several economic indicators that characterize the cost-effectiveness and relative magnitude of conservation retrofit investment, including simple payback time (SPT), cost of conserved energy (CCE), and an investment index.[7,8] SPT is defined as:

$$SPT = \frac{FC}{(\Delta E * P) - \Delta OMC} \tag{1}$$

where:

FC	= first cost of retrofit
ΔE	= energy savings (based on first-year savings)
P	= local energy price
ΔOMC	= increase in first-year operations and maintenance costs.

We also calculated the CCE, which compares conservation investments to purchases of fuel or electricity, and provides a societal perspective on retrofit investments. CCE is found by dividing the annualized cost of the retrofit by the annual energy savings. It can be expressed as:

$$CCE = \frac{FC * CRF + \Delta OMC}{\Delta E} \tag{2}$$

where:

$$CRF = capital\ recovery\ factor = \frac{d}{1-(1+d)^{-n}}$$

d	= discount rate
n	= lifetime of measures

Conservation investments are amortized over the measures' expected physical lifetimes, using a real (or constant dollar) discount rate of seven percent. The CCE formula implicitly assumes constant (1987$) energy prices.

We defined the investment index for each project as the ratio of the first cost of the retrofit to annual pre-retrofit energy expenditures. This can be interpreted as "the number of years of energy expenses" invested in a retrofit project.

† We had information on vacancy rates for 34 buildings.

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. Table 1 compares structural and demographic characteristics of buildings in the data base with values for the U.S. stock.† 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).[9]

Table 1 also provides a detailed breakdown of key characteristics of buildings in this study. Fifty-eight percent of the buildings have between 10 and 50 units, while only nine percent have more than 100 units. Almost 80% of the buildings are low-rise structures, and more than 50% of the 37 high-rise buildings are managed by public housing authorities (PHA). Almost three-quarters of the projects have between 500 and 1000 ft^2 per apartment.

Gas is the most common space heating fuel (55%) in our sample, followed by electricity (22%). With few exceptions, buildings in our data base that heat with electricity are located in the Pacific Northwest and have low-rise, wood-frame construction. A majority of the buildings that heat with oil are public housing projects. Almost all fuel-heat buildings in the data base have central boilers and master meters. Electric-heat buildings typically have baseboard resistance heating in apartments that are individually metered. Older buildings generally use gas or oil for heating (e.g., 65% of the fuel-heat buildings were built before 1960); electric heating is common in newer buildings.

Our sample of buildings is somewhat skewed with respect to geographic location, with clusters of buildings in a few regions. For example, 65 buildings are located in the Minneapolis-St. Paul area, 52 retrofit projects are in the New York City-New Jersey-Philadelphia area, 39 projects are in the Pacific Northwest, while 20 buildings are located in Chicago and 11 in San Francisco. To a great extent, this clustering reflects those areas of the country with organizations or utilities that have played a leading role in developing retrofit programs for the multifamily sector, and have documented their results.

† Stock values are for *households* living in buildings with five or more units. In assessing the representativeness of our sample, it might be preferable to compare it with the stock of multifamily buildings that have been retrofitted. However, we are not aware of any characteristics data for all multifamily buildings retrofitted during the last decade.

Table 1. 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. Approximately 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 above categories.

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/unit, and fuel-heat buildings used 86 MBtu (10^6 Btu) per dwelling 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, even when fuel-heat buildings are binned into similar climate zones.

Because of limitations in the RECS consumption data for the multifamily sector, we included in Fig. 1 regional studies from Seattle and Minneapolis that reported baseline energy consumption from large samples of multifamily buildings (71 and 174 buildings, respectively).[10,11] Pre-retrofit consumption of electric-heat buildings and fuel-heat buildings with hot water distribution systems in this study are comparable to baseline consumption of similar Seattle and Minneapolis multifamily buildings. One exception is the higher initial consumption of fuel-heat buildings with steam heating distribution systems in our sample, compared to the Minneapolis baseline. This results from the relatively large fraction of steam-heat buildings in our study that are public housing projects, which tend to be inefficient relative to the privately-owned multifamily stock.

Retrofit Measures and Costs

In general, retrofit efforts focused on reducing space heating and domestic hot water (DHW) energy use (see Appendix C for description of measures). However, the choice and frequency of measures installed varied, depending on heating equipment and fuel (Fig. 2). In addition, retrofit strategies pursued in public housing projects are shown separately, to illustrate the relatively greater emphasis on window and boiler replacements, which tend to be more expensive. 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 and new burners) were added to 35% of these buildings. In contrast, retrofit efforts in electric-heat buildings were directed mainly toward 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 about 50% of the electric-heat buildings; in contrast,

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† We used the 1984 Residential Energy Consumption Survey (RECS) public-use data tape to calculate energy consumption of the space heat fuel for gas- and oil-heated multifamily buildings with five or more units. Note that in RECS survey from which stock values were calculated, only 18% of the fuel records were usable for multifamily buildings with five or more units. RECS did not obtain fuel records if energy bills were included in a household's rent or paid in other ways (effectively excluding all master-metered buildings); thus, fuel consumption was primarily determined from single-family and small multifamily buildings.

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 of both long estimated payback times, as compared to many system retrofits, and to the existence of structural barriers which limit the applicability of 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. Figure 3 shows that system retrofits, at a median cost of $150/unit, were much less expensive than either shell measures or combined system and shell retrofit packages, with median costs of $1,350-1,500/unit. As noted earlier, shell retrofits were more common in electric-heat buildings. 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 retrofit of the existing stock and subsidized some or all of the installation costs. For example, owners that participated in Seattle City Light's Multifamily Research and Demonstration (R&D) project paid only 25% of the cost of weatherization, while the utility paid 75%.[12] The Bonneville Power Administration (BPA), sponsor of the Hood River Conservation Project, paid the entire cost of retrofits, because BPA wanted to test the reasonable upper limits of a residential weatherization program.[13]

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 2). The organizations that initiated these programs were located mainly in the Midwest and Pacific Northwest. Installed 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 costs for these retrofits 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 (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 index = 1.7 for public housing versus 0.4 for privately-owned 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 company contracts that guarantee savings or maximum energy bills after retrofit).

Table 2. 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 (3)	5550 - 7700 per bldg.		low=space heat system only, high=space heat & DHW systems
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".

RESULTS

Energy Savings

Median annual energy consumption decreased by 14 MBtu (10^6 Btu) per dwelling unit after retrofit in fuel-heat buildings and by 1450 kWh/unit in electric-heat buildings. The percentage reduction from pre-retrofit usage was comparable in the two groups (16% and 14%, respectively).† The percent reduction in space heating use alone is significantly higher, but difficult to estimate reliably with only utility billing data, even using the PRISM regression model.‡ Energy savings were between 10 and 30% of pre-retrofit use in 60% of the projects (Fig. 4), and were somewhat correlated with energy consumption prior to retrofit (r= 0.66). Buildings with high percentage savings tended to be those that were very energy-intensive to begin with, often because of poorly-controlled boilers and distribution systems. Figure 4 also suggests that energy savings are highly variable; in a few cases, weather-normalized consumption actually increased after retrofit.

The choice of retrofit measure/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, when necessary, grouped simultaneous retrofits in a specific building into broader categories (heating/hot water system packages, shell packages, and "system and shell" packages). Figure 5 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 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 ($2100/unit) and typically saved 17-31 MBtu/unit, with a payback time of 10 years. "Shell and system" packages, which were installed in 25 buildings, were the most comprehensive retrofit efforts. They saved 26% of pre-retrofit energy use with an initial investment of about $1,000/unit, resulting in a simple payback time of six years.

Retrofit economics were generally less favorable in our small sample of electric-heat buildings (Fig. 6). The dominant retrofit strategies, shell and window measures, had payback times between 18 and 23 years. In these buildings, percentage savings were comparable to those from low-cost heating system and control retrofits in fuel-heat buildings; however, shell and window retrofit costs were much higher ($1,000-1,400/unit). Figure 6 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, the attractiveness of discounted bulk rates offered by the utilities compared to residential rates, and lower construction costs (compared to installation of individual electric meters).[14] Tenants in the New York projects

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

‡ An estimate of the temperature-dependent consumption and savings (often used as a proxy for space heat consumption) is provided by PRISM ; however, we rely instead on the NAC index because it is statistically robust compared to the estimate for the temperature-dependent variable (standard errors of the NAC are typically 3-4%, while they are often 10-20% for the temperature-dependent term in the model).

reduced lighting and appliance electricity consumption by 18% in four apartment complexes after installation of various submetering technologies (e.g., electronic metering using carrier wave technology for communications). The metering conversions were not strictly a technical efficiency measure, since reduction in energy use was a result of changes in occupant behavior.

Savings from Individual Measures

Although typical retrofit practice is to install several measures concurrently, we have compiled data for a subsample of buildings in which individual measures were implemented (see Table 3). In some cases, retrofit measures were tailored to specific heating systems. For example, *outdoor reset and cutout controls* were installed in 21 low-rise apartment buildings with gas-fired hydronic boilers and baseboard radiators; most of these buildings participated in a monitoring project initiated by the Minneapolis Energy Office.[15,16] An outdoor reset varies the water temperature in the distribution system (typically about 180-200^{o}F) inversely with outdoor temperature, as opposed to an "aquastat" control, which maintains a constant boiler water temperature. The outdoor cutout turns off the heating system during the spring and fall months when the outdoor temperature is above a specified level. Initial costs for this retrofit were quite low ($10-20/unit), energy savings were significant (approximately nine percent), and paybacks were very short (roughly one year).

Table 3. Cost-effective individual retrofit measures.[a]

Retrofit Strategy	*Location*	*Number of Projects [No. of Units]*	*Annual Energy Savings (MBtu/unit)*	*(%)*	*SPT (years)*
Outdoor Reset/ Cutout Controls	MN, NJ, PA	21 [1677]	4 ± 1	9	0.9 ± 0.5
Electronic Vent Dampers	MN	7 [148]	4 ± 1	7	5.7 ± 13.9
Front-End Boiler	MN	4 [76]	8 ± 3	12	9.4 ± 1.4
Steam Balancing	MN	13 [263]	14 ± 6	13	1.5 ± 0.6
Steam to Hot Water Conversion	MN	7 [118]	24 ± 13	25	7.3 ± 3.5
Energy Management System	GA, MN, NJ, NY	4 [2344]	27 ± 21	25	2.5 ± 1.7

[a] Results are given as median ± standard error.

Vent dampers were installed in five hot-water-heated buildings and two steam-heated buildings. Heating systems were run alternately, at two-week intervals, with the vent dampers operating and then deactivated in a well-monitored experiment during two heating seasons.[17] Median savings from the vent dampers were about seven percent of total gas consumption; space heat energy use was reduced by 11-16%.† Overall, paybacks were about six years, although the retrofit was more cost-effective in the steam-heated buildings, which had three-year paybacks.

After installation of outdoor resets/cutouts and vent dampers, *modular front-end boilers* offer another (albeit more expensive) way to improve heating system efficiency in buildings with hydronic distribution systems. A front-end boiler is a high-efficiency boiler installed to supplement an existing (and presumably less efficient) boiler. A front-end boiler is typically sized to meet 25-50% of maximum demand, but can often supply from 60-90% of the annual heating load in Minnesota (because the majority of the space heat load occurs during relatively moderate weather). A front-end boiler installation can also be modified slightly to provide domestic hot water (with additional controls, pumps, and a heat exchanger), which improves the economics of the retrofit. Installation of front-end boilers reduced space heat and hot water consumption by 12% in four Minnesota buildings (with space heat savings of 15-18%). Paybacks were fairly long (about 10 years) in these buildings; the Minnesota study concluded that economics could be improved somewhat by targeting larger buildings (space heat load in excess of 500 MBtu/building-year), buildings with inefficient existing boilers (annual efficiency of less than 70%), and buildings with large DHW savings potential.[18,19]

A *balancing program* for the heat distribution system was particularly effective in older buildings with steam distribution systems. Steam balancing attempts to minimize the problem of uneven heating, which is usually caused by large differences in steam arrival times at radiators in a building, excessively short boiler cycles, and the absence of temperature controls in individual units. This leads to excessive indoor temperatures in some apartments, which result in greater heat losses as tenants open windows. The steam balancing techniques employed in 13 buildings included the following measures: 1) larger main-line air vents, 2) new boiler controls which effectively lengthen the boiler cycle, 3) oversized radiator vents on radiators that are located a significant distance from the boiler, and 4) occasional use of thermostatic radiator vents to improve individual unit temperature control.[20] Boilers were cleaned and tuned at three of the sites. Annual gas savings averaged 14 MBtu/unit in these buildings, or 13% of pre-retrofit consumption. Payback times ranged from several months to four years for the twelve buildings that realized savings.

Converting the existing steam distribution system to a modern hot water system is a more expensive retrofit option for older buildings. The retrofit can be attractive when boilers are replaced in buildings with two-pipe steam systems (i.e., separate steam and condensate pipes) because the existing distribution system can be retained, which greatly reduces costs.† Gas consumption decreased by 25% after this retrofit in seven buildings. Payback times ranged from 7-28 years in buildings with single-pipe steam systems; paybacks were less than five years in two of the three two-pipe steam buildings.

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† Savings represent averages over the two-year period; the authors reported that savings results were inconsistent between the two years for several of the buildings.

† Conversion costs in two-pipe steam buildings ranged from $500-900/unit, versus $1500-3800/unit in single-pipe steam buildings.

Determinants of Energy Savings

We also used multivariate regression analysis to determine which characteristics had the most influence on the magnitude of energy savings in our sample of retrofitted multifamily buildings. We used a two-stage process to analyze factors related to energy savings, similar to the method suggested by Hirst.[21] First, we assumed that the PRISM model removes the effects of short-term changes in weather on energy savings, as reflected in the normalized annual consumption (NAC) index. We used the change in NAC before and after retrofit at each building as the dependent variable, representing energy savings in a year with typical weather.† In the regression model, site 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. Factors thought to influence energy savings in multifamily buildings include retrofit characteristics, the condition of the building envelope and equipment before retrofit, occupant/ownership characteristics, climate severity, and energy use and prices. However, detailed information was not available on all of these characteristics for buildings in our sample. Independent variables included in the initial regression analysis are listed in Table 4.§

† An alternative to this approach is to analyze changes in energy demand using the monthly billing data, actual heating degree-days, and all other explanatory variables in a ''single-stage'' model.

‡ Electricity is expressed in terms of site energy (3413 Btu = 1 kWh); we used savings/ft^2 as the dependent variable, rather than savings/dwelling unit, because the former was distributed more normally for our projects.

Table 4. 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 3413 Btu=1 kWh.

Because most buildings were master-metered, we only included characteristics that were applicable at the building (as opposed to the apartment) level. Most of the independent variables in

§ We included all variables for which information was available from at least 90% of the buildings in the sample. Typical values for the entire sample were assigned in the few cases where information on a particular characteristic was missing; when this was not possible, pairwise deletion of missing variables was used.

the regression equations were "dummy variables", indicating the presence or 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 ten 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.† One hundred seventy-three retrofit projects (137 fuel-heat projects and 36 electric-heat buildings) were included in the final analysis. Projects were excluded for the following reasons: Too many missing values for key variables, buildings with extensive structural renovation or rehabilitation costs, and retrofits that targeted only secondary end uses (e.g., lighting). The final regression models include all variables 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 5). In fuel-heat buildings, *pre-retrofit use* alone accounted for 37% of the variation in savings. In contrast, pre-retrofit energy use in electric-heat buildings, although significant, was much less influential in explaining variations in savings. In this group of buildings, *retrofit cost* alone accounted for almost 40% of the variation in savings. As noted previously, there was not much variation in pre-retrofit electricity consumption among electric-heat buildings, as they were all located in the Pacific Northwest and were of similar construction. This explains why consumption prior to retrofit was not an important determinant of savings for these buildings. In contrast, the larger sample of fuel-heat buildings spanned all major climate zones and included more varied building types; not surprisingly, there was much greater variation in pre-retrofit energy consumption in these buildings. 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 larger levels of investment in retrofits.

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† We decided not to combine fuel- and electric-heat buildings in the same equation, because this approach constrained the error variance to be the same for savings obtained in both groups of buildings. Our analysis suggested that the error variance was significantly different for fuel- and electric-heat buildings. For example, both energy consumption prior to retrofit and savings were much more varied in fuel-heat buildings compared to electric-heat buildings.

‡ Non-significant alternates of significant dummy variables were also kept in the equation. Since coefficients for dummy variables are always with respect to the "reference case", simply eliminating these 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 those buildings all received window retrofits.

Table 5. 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 explanatory variable. Outliers were identified for each of the models, and their degree of influence was assessed using Mahalanobis' distance (a measure of how far the case is from the average values) and Cook's distance (a measure of the case's influence in determining the regression model) (Norusis, 1985). One influential outlier was removed from the fuel-heated models. 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.

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 greater than those from the least effective retrofit strategies. 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 least effective retrofits (i.e., 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/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/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 ranked the retrofit strategies by their coefficients, as obtained from the regression analysis, and compared that with a ranking of measures based on a simple calculation of average savings for each retrofit strategy (i.e., cross-tabulation). The same four measures (i.e., boiler retrofits, "shell and system" combinations, energy management systems, and distribution system conversions) saved the most energy in fuel-heat buildings, although their order was different. However, heating controls and solar hot water retrofits, as opposed to shell measures, saved the least energy when ranked by cross-tabulation. In electric-heat buildings, shell measures were ranked first by the cross-tabulation, followed by "shell and system" packages and, finally, window retrofits. In contrast, the ranking of measures was window retrofits, shell packages, and then "system and shell" packages, based on results of the regression analysis. The regression analysis provides some new insights on the relative influence of particular retrofit strategies in accounting for variation in savings that are not accurately reflected by a simple cross-tabulation of savings by strategy.

Relative energy prices were included in the model, as they were thought to be an indirect proxy for savings potential. For example, more intensive retrofits would be economical in regions with high energy prices, or the building stock could be relatively less efficient in regions with historically low energy prices. Energy price was a significant explanatory variable only in

† Factors that contributed to the narrow range of strategies include our limited sample and a small number of retrofit options available for buildings with electric resistance heating.

‡ These parameter estimates might be more logically consistent if we had a larger data set.

electric-heat buildings (savings were 1.4 kBtu/ft^2 higher for every dollar per MBtu increase in energy price). However, our electric-heat buildings were located in only three regions; therefore, these results should be interpreted with some caution. We believe the price variable could reflect differences in retrofit programs in the three regions, rather than any actual influence of energy prices on savings.†

Pre-retrofit energy consumption and building structure/equipment characteristics are both possible indicators of savings potential. In general, we found that the structural variables that, in theory, could be useful proxies for high savings (e.g., year built, central heating system, masonry/frame construction) were not significant; thus, they do not appear in the final model. Unfortunately, other variables that might more directly signal savings potential (e.g., low heating system efficiency or poor insulation levels) were unknown for many of our projects.

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 both models for the electric-heat buildings. For the fuel-heat buildings, retrofit cost became statistically significant and choice of retrofit strategy explained the most variation in savings. For example, "shell and system" retrofits alone explained 27% of the variation in savings.

A number of variables included in the initial equations were not statistically significant in any of the models. For example, energy savings were not strongly influenced by climate severity, as measured by long-term average heating degree-days (HDD). For the group of electric-heat buildings, this can easily be explained because almost all of the buildings were located in similar climate regions. For fuel-heat buildings, HDD were also not significant, principally because our sample included a large group of private-sector buildings in Minnesota (a severe heating climate) that were relatively energy-efficient prior to retrofit and that participated in programs that focused only on low-cost, short-payback retrofits.

† The fact that energy costs are often not paid directly by occupants further complicates interpretation of relative prices or changes in energy prices.

‡ In addition, building owners, conservation program managers, or auditors often may not have access to existing consumption data to use in assessing the potential for savings from conservation retrofits at various sites.

Persistence of Savings

Energy savings are typically tracked for only one year after retrofit. However, several years of post-retrofit utility bills were available for 26 projects. The following retrofit strategies were represented among these projects: Various shell retrofits [7], heating system measures [9], tenant metering systems [9], and both shell and system changes [1].† The tenant metering systems were installed in fuel-heat buildings that had hot-water baseboard heating systems and individual zone control of the flow of hot water into each apartment.[22] 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 divided the energy bill among individual apartments on the basis of use.‡

Table 6 shows the absolute and percentage changes in weather-normalized annual consumption for the 26 projects in the first, second, and third post-retrofit years. Savings in years two and three are calculated relative to the pre-retrofit year. Energy savings in years two and three either increased or remained at first-year levels at 17 of the 26 projects; savings decreased at nine projects. However, in most cases, the changes in savings in year two and three were not statistically significant (95% confidence level). Energy savings increased significantly at two of the nine Minnesota buildings that installed individual-unit tenant-metering systems (16 and 19%), and at one building in Seattle that received various shell measures (9%). The results at the Seattle building were expected because the utility had identified problems with the contractor's initial installation; thus expected savings were not fully realized until the third year when the problems were remedied. At the two Minnesota buildings, energy consumption during the first post-retrofit heating season was still much higher than all but one of the other seven buildings. Because tenants at these sites paid their energy bills directly after the metering conversion, they were motivated to reduce energy consumption; by the end of the second year, additional savings were achieved as consumption levels were no longer excessively high compared to those in similar buildings.

At two public housing projects, energy savings decreased significantly in the second year after retrofit. We do not have data to explain these changes. Anecdotal evidence suggests that inadequate maintenance may be responsible for the deterioration in energy savings at the Trenton site. This is a serious problem in older steam-heat buildings.[23] These preliminary results suggest that operations and maintenance efforts are particularly important for preserving initial energy savings from heating system retrofits. Continued tracking of the performance of conservation retrofits is recommended to ensure that first-year savings continue over a measure's expected lifetime.

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† Number of projects is in brackets.

‡ The effect of tenant metering on individual tenants' energy costs 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 tenants' total costs can increase significantly.

Table 6. Persistence of savings.[a]

Location	*Strategy*[b]	*Pre*	*Savings Year 1*	*Savings Year 2*	*Savings Year 3*	*% Savings Year 1*	*% Savings Year 2*	*% Savings Year 3*
		(kWh/unit)	*(kWh/unit)*					
Seattle WA	SH	13062	507	652	1731 **	4	5	13
		8151	1912 **	1918	2148	24	24	26
		9122	1290 **	1487	1659	14	16	18
Newark DE	HD	11543	1600 **	990		14	9	
		(MBtu/unit)	*(MBtu/unit)*					
San Fran. CA	SH	93	8 **	11		8	12	
		135	23 **	22		17	16	
		87	9 **	-1 **		11	-1	
Minn. MN[c]	VDE	50	6	4		12	8	
		140	18	5		13	4	
		32	3	3		10	10	
		37	1	4		3	11	
Atlanta GA	EM	136	44 **	43		32	32	
Asbury Park NJ	BR	211	109 **	112		52	53	
New York NY	EM,WR	85	1	3		1	4	
Trenton NJ	BR,HC	188	58 **	50	49	31	27	26
		199	44 **	23 **	17	22	12	9
		182	10	25		5	14	
Minn. MN	MC	122	20 **	24		16	20	
		78	10 **	9		13	12	
		125	26 **	42 **		21	34	
		59	11 **	11		18	18	
		57	11 **	12		20	21	
		45	6 **	7		13	16	
		48	5 **	8		11	17	
		99	9 **	9		9	9	
		132	28 **	48 **		21	36	

** Savings are significant at 95% level.

[a] Savings for years 1, 2, and 3 are calculated relative to pre-retrofit consumption.

[b] Strategies: SH=shell, HD=house doctor, VDE=electronic vent dampers, EM=energy management system, HR=central boiler relaced with individual apartment heating units, WR=window replacement, BR=boiler replacement and heating controls, MC=installation of tenant metering system in master-metered building.

[c] Percentage savings are for space heat use only.

Predicted versus Measured Energy Savings

Energy audits performed for 54 retrofit projects were used, along with building energy analysis models, to estimate energy savings. These building audits occurred in quite different contexts, including: 1) the audit and marketing component of a residential or multifamily conservation program (e.g., BPA's Hood River project, Minneapolis Energy Office, Chicago Energy Savers Fund), 2) engineering analysis of savings potential as part of a shared-savings agreement (St. Paul, Philadelphia), or 3) as an element of a research/demonstration project. The complexity of the model used in these prediction efforts depended to some extent on their intended use. In general, audits performed by a shared-savings company or research project were more detailed and utilized more sophisticated building energy analysis models than audits done for other programs. For example, the building energy audit/retrofit performance process followed by St. Paul's Energy Resource Center (ERC) included elements that are not typically part of most multifamily conservation programs: 1) careful application of a building energy simulation program that calculates monthly building loads (including calibration of calculated performance with weather-normalized pre-retrofit utility bills by adjusting the building input parameters), 2) reliance on an experienced mechanical engineer for savings estimates from heating/hot water system improvements, and 3) quality control during the retrofit process (ERC monitored the buildings closely and made additional site visits to fine-tune the heating system in buildings where monthly bills indicated that energy savings were less than predicted). These factors undoubtedly contributed to the relatively close agreement between estimated and actual energy savings for the group of 11 buildings (22 versus 28 MBtu/unit).

With the exception of the Hood River buildings, we found that, median values for measured savings were equal to or greater than estimated savings, averaged for each group of buildings (Fig. 7). However, Fig. 7 also shows that relatively good agreement between predicted and measured average savings often masks large discrepancies for individual buildings. For example, on average, predicted and measured savings agreed closely in four Seattle buildings (5 MBtu/unit), although the discrepancy was at least ±20% for each individual building. In contrast, the relatively close agreement between predicted and actual median savings for the group of St. Paul buildings is also observed among individual buildings: predicted and measured savings agreed within ±20% for seven of the 11 St. Paul buildings. At Hood River, measured savings were systematically below predicted levels. The results for the small sample of multifamily units in Hood River (432 units in 21 projects) are similar to those for the complete sample of almost 3000 (mostly single-family) households: actual savings averaged only 43% of those predicted by energy audits.[24] This difference was attributed to pre-program reductions in electricity use and to post-program changes in energy-related behavior (e.g., higher indoor temperatures and less use of wood) as well as other factors.†

Estimation of Stockwide Savings Potential

We estimated the nationwide energy saving potential using the measured results from multifamily retrofits.[25] 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 most multifamily building owners would be

† These discrepancies include errors in audit methodology, data collection and interpretation, poor installation quality, and limitations in the building simulation model. For example, the Hood River audit computed potential savings based on analysis of homes that used much more electricity than houses in Hood River used.

willing to invest in retrofits under current market conditions. Owners generally will not invest in "intensive" retrofit packages without incentives from government or utilities or some sharing of risks. We made separate estimates of stockwide savings potential for four major market segments: 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 (see Fig. 8).

Median fuel savings for typical retrofit efforts in fuel-heat buildings with central heating systems 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% of pre-retrofit fuel consumption for fuel-heat buildings with individual unit heating, although our sample is relatively small. Finally, median electricity savings were 10% and 19%, respectively, for typical and intensive retrofit packages in individually-metered buildings with electric baseboard heating.

The measured savings for each group were extrapolated to the U.S. multifamily stock using information on consumption and building characteristics 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 type, fuel type, and vintage. Savings for 2-4 unit buildings are based on savings obtained in 5+ unit buildings with similar characteristics. Our analysis accounted for the disproportionately large number of multifamily buildings in the sample that are located in colder climates and the fact that these buildings used more energy prior to retrofit than the U.S. multifamily stock (even after correcting for climate differences).

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 were 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. 9).‡ These results suggest that current energy consumption of the space heat fuel in the multifamily sector could easily be reduced by 9-22% based on documented results from existing conservation programs.† Based

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† Because RECS does not collect data on distribution system type, we assumed that centrally-heated fuel buildings built prior to 1950 have steam distribution systems, while those built after 1950 use hot water distribution. We assumed that most buildings constructed since 1980 were not eligible for retrofitting because of more energy-efficient design standards included in recent building codes.

‡ Electricity is expressed in terms of resource energy (11,500 Btu = 1 kWh).

† Stock savings are calculated by multiplying floor area for each market segment by savings/ft^2 for typical and intensive retrofit packages. Percent savings are calculated by taking the stock savings estimates for typical and intensive retrofits divided by the energy consumption of the main heating fuel for all multifamily buildings (2.38 quads in

on actual costs for buildings in the data base, we estimated that retrofitting the entire multifamily stock with ''typical'' retrofit packages would cost about \$7.5 - \$11 billion; for the intensive retrofits, \$27 - \$32 billion.‡

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. 9). 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 database to the stock are correct (i.e., we have not left out any significant adjustments, such as corrections for indoor temperatures, occupant behavior, etc.) We also performed a less rigorous assessment of the reasonableness of our assumptions (e.g., the correctness of assuming that savings in 5+ unit buildings apply equally well to 2-4 unit buildings). We compared the measured savings from retrofitted multifamily buildings with retrofit performance in single family houses (for the 2-4 unit buildings); stockwide savings from typical retrofits increased by 0.06 quads.

This analysis 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 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.[4] Despite the limitations of these studies as well as uncertainties in our extrapolation, our assessment is that, at present, retrofit results appear to fall short of the achievable ''best practice.''

The gap between actual results and theoretical potential is related to the following factors: i) thoroughness (i.e., implementation of all feasible and economic measures in a given building or subset of the stock), ii) quality (i.e., actual performance of measures over time as a function of product quality, installation, and maintenance), and iii) coverage (i.e., extent of retrofitting of the ''eligible'' stock). One or more of these issues tends to surface when examining any particular subset of the multifamily stock. For example, we found that retrofit practice in fuel-heat buildings that are privately-owned is often characterized by ''cream-skimming.'' This is, in a sense, the opposite of ''thoroughness;'' only measures with very short paybacks are selected, with little regard for viable but longer-payback measures. In contrast, a common problem in public housing is that local housing authorities often bypass the cost-effective measures, instead selecting very capital-intensive retrofits that can be financed as part of a general renovation project; these may not be the retrofits with the greatest payback per dollar invested. Another problem of

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resource energy). This approach is quite conservative, because the main heating fuel includes other end uses in almost all households. The percent reduction in space heating is much higher, but difficult to estimate with only utility billing data.

‡ This estimate includes materials and contractor labor costs for the retrofit; it does not include any conservation program administration costs.

''thoroughness'' is that retrofit efforts in the multifamily sector have focused principally on reducing space heat and domestic hot water energy use. There is little documented evidence about retrofits that attempt to reduce consumption for cooling (e.g., efficiency improvements in individual-unit air conditioners, heat pumps, retrofits to windows to control solar gain in cooling climates), lighting, appliances, or miscellaneous end uses (laundry areas and pools). On the issue of retrofit ''quality'', we note that, in all sectors, energy management efforts have traditionally been biased against operation and maintenance activities. In addition, building owners are often reluctant to commit the necessary O&M resources to achieve maximum performance from hardware retrofits. Finally, on the issue of ''coverage,'' landlords and tenants have historically been reluctant to invest in retrofits, which continues to limit penetration rates.

CONCLUSION

Table 7 summarizes key quantitative results from this study. 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. Regression models for fuel- and electric-heat buildings explained about 60% of the observed variation in energy savings. Factors that contributed to the large variation in energy savings were pre-retrofit usage, size of investment, and choice of retrofit strategy.

On a per-unit basis, retrofit costs were much lower in fuel-heat buildings than in 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 (i.e., electric-heat buildings were smaller than fuel-heat buildings). Our results reinforce the view that private multifamily building owners seldom make substantial investments in conservation; median retrofit costs for privately-owned fuel-heat buildings were only 40% of annual energy costs.

We also found that 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. Outdoor resets and cutout controls were especially cost-effective in buildings with hot water distribution systems, as was steam balancing in buildings with steam distribution systems. 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. Based on the commonly chosen retrofit options and current program experience in electric-heat buildings, our results suggest that it is not cost-effective to spend more than $2,000/unit. Program economics could be improved by limiting costs, targeting high users, and emphasizing less expensive retrofits, including lighting and DHW measures.

Table 7. Summary of savings and economic indicators.[a]

	All Buildings	*Fuel Heat (private)*	*Fuel Heat (PHA)*	*Electric Heat*
Number of Retrofit Projects	191	111	38	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 (years)	7 ± 1	4 ± 1	10 ± 4	23 ± 7
CCE[b] (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 3413 Btu=1 kWh.

Extrapolating these documented retrofit results to the U.S. multifamily stock, we found that between 0.2 and 0.5 quads of resource energy 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. Analyses of the retrofit data compiled thus far suggest several important questions that require better data and continuing analysis. First, tracking the performance of retrofits over several years continues to be a high priority, since retrofit cost-effectiveness often assumes that savings will persist for at least 5-10 years. However, even when energy use data are available for several years, long-term tracking of occupied buildings is difficult, because the problems of accounting for changes in operating conditions, occupancy, and the effects of additional retrofits are magnified as the monitoring period increases. Second, electric utilities in some regions (notably the Northeast) are increasingly concerned with both winter and summer peak demand; the load-profile impacts of residential retrofits, including not only conventional space and water heating measures, but also efficient appliances, storage heating, and equipment and shell improvements aimed at reduced cooling energy, all need to be measured and evaluated. Better data from end-use load-profile monitoring projects would contribute greatly to our understanding of residential retrofit impacts. Finally, new retrofit technologies are constantly being introduced to the market; for many of these products (such as low-emissivity "heat mirror" windows and advanced electronic controls for space conditioning equipment and appliances), actual performance under realistic operating conditions has yet to be measured and documented.

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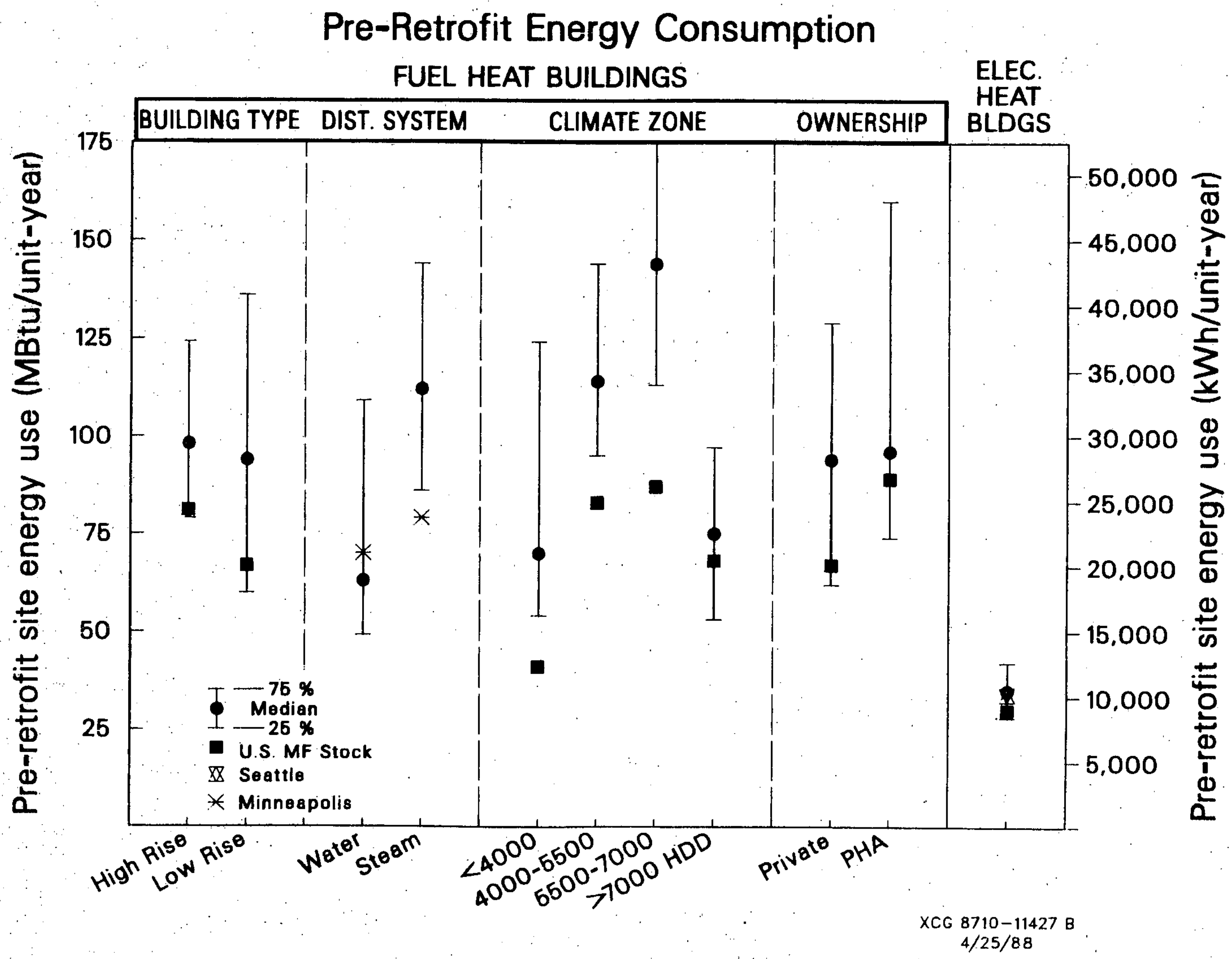

Fig. 1. Pre-retrofit energy consumption of multifamily buildings in this study compared to medians for the multifamily stock (with five or more units). Interquartile range in energy consumption is shown for fuel-heat buildings that are privately-owned or managed by public housing authorities (PHA) and for electric-heat buildings. 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).
Sources: U.S. stock [Ref. 3]; Seattle stock [Ref. 11]; Minneapolis stock [Ref. 12].

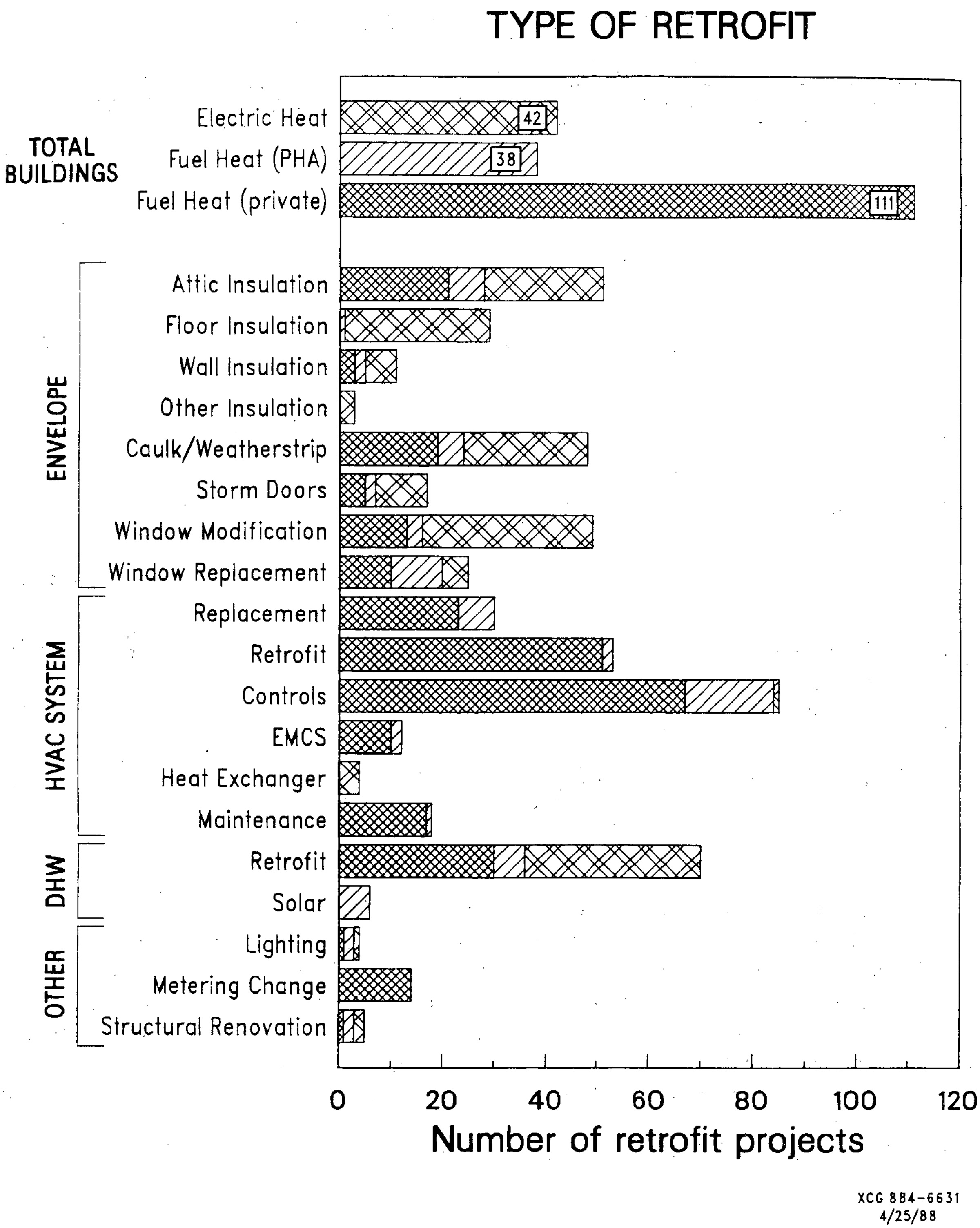

Fig. 2. Relative frequency with which retrofit measures were installed in multifamily buildings. Total number of buildings is shown at top; note that the cumulative total of measures is much greater than the total number of buildings because more than one measure is often installed in an individual building.

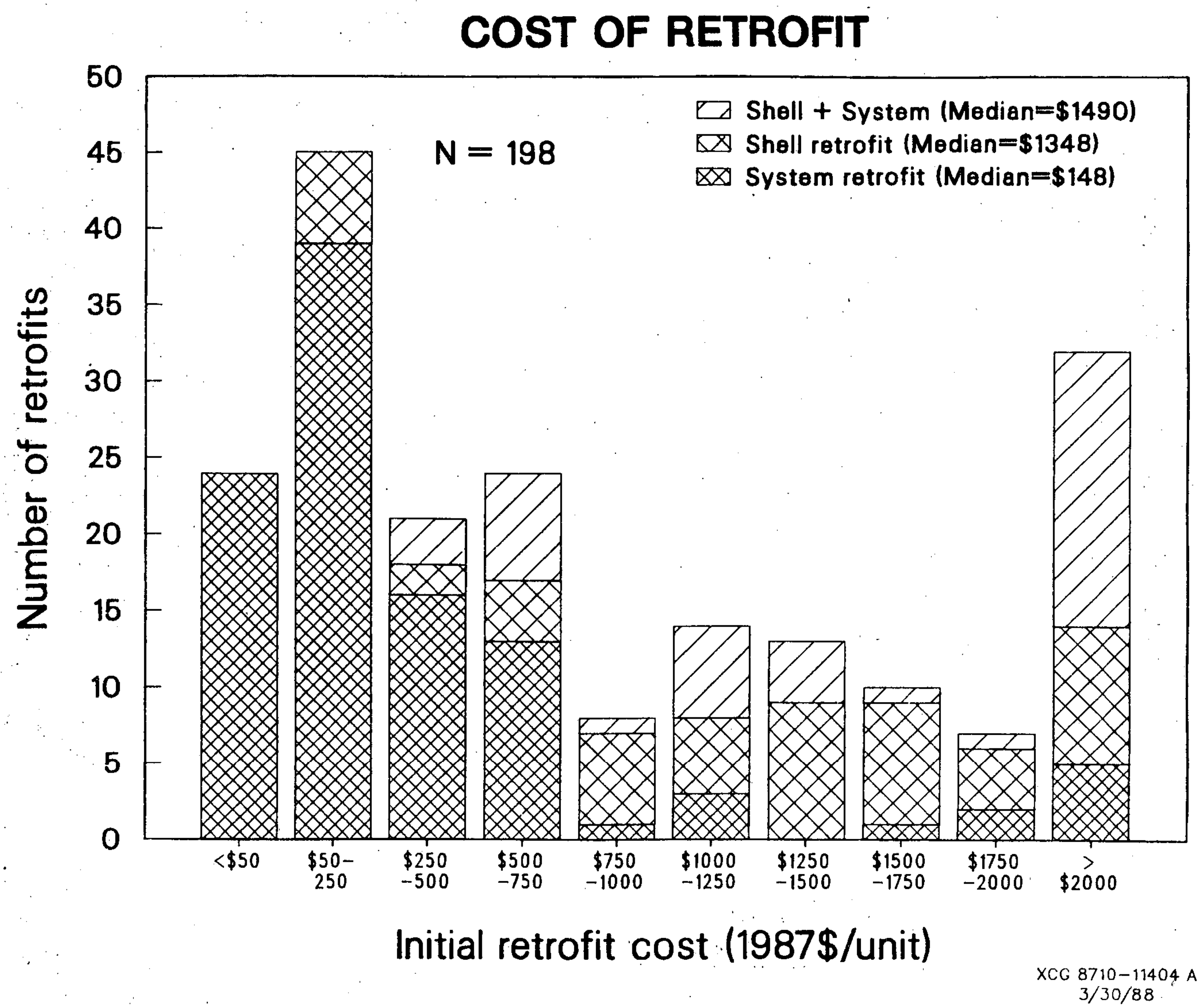

Fig. 3. Distribution of retrofit costs, expressed in 1987 $/apartment unit, for the 198 retrofits in this study.

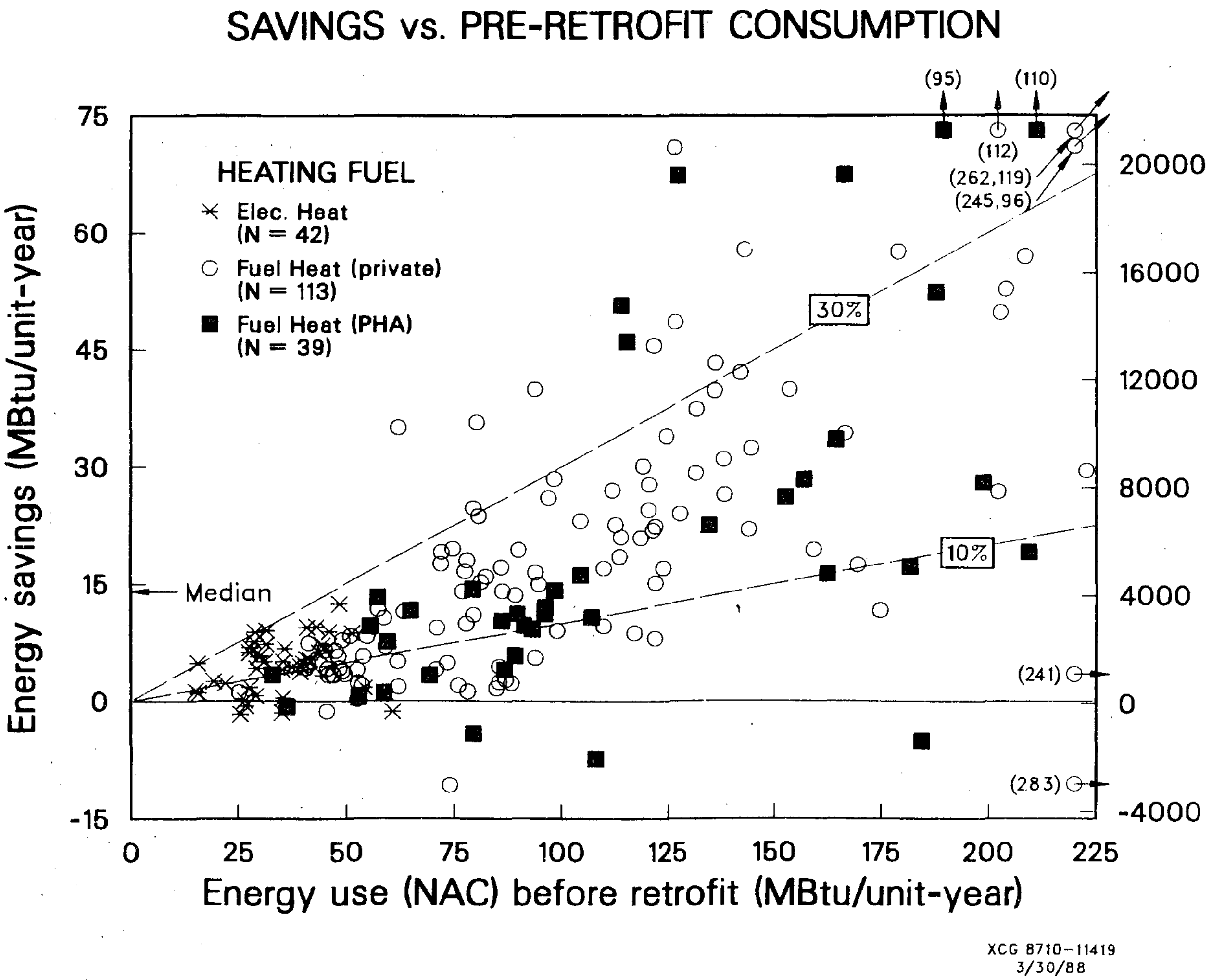

Fig. 4. Plot of energy savings as a function of weather-normalized annual energy consumption (NAC) prior to retrofit, grouped by heating fuel and ownership. Electricity use is expressed in terms of site energy, 3,413 Btu per kWh.

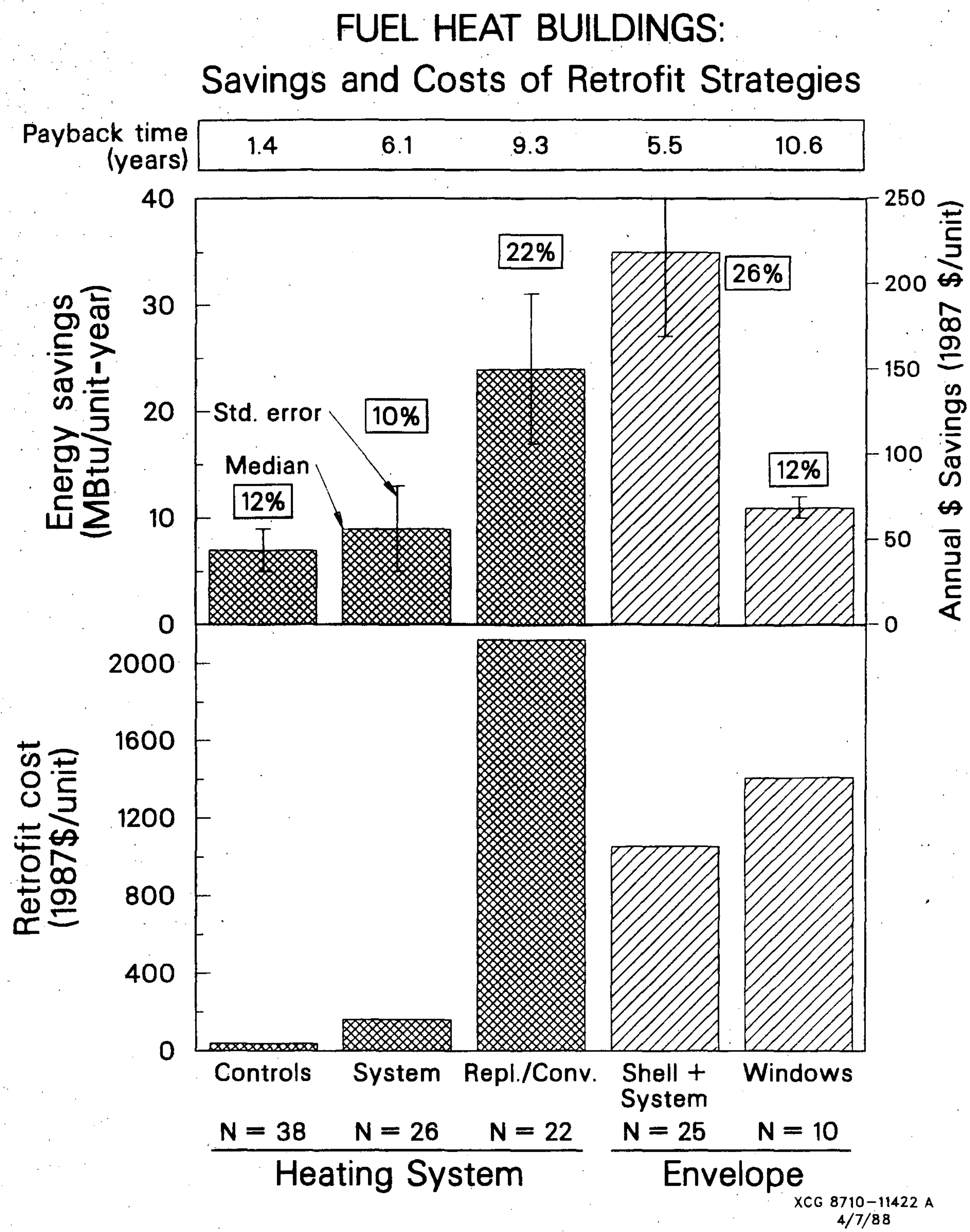

Fig. 5. Energy savings, retrofit cost, and median payback time of various retrofit strategies in fuel-heat multifamily buildings. *System* retrofits are groups of measures that affect the heating or hot water systems. *Repl./Conv.* include boiler replacements or conversions from steam to hot water distribution. *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).

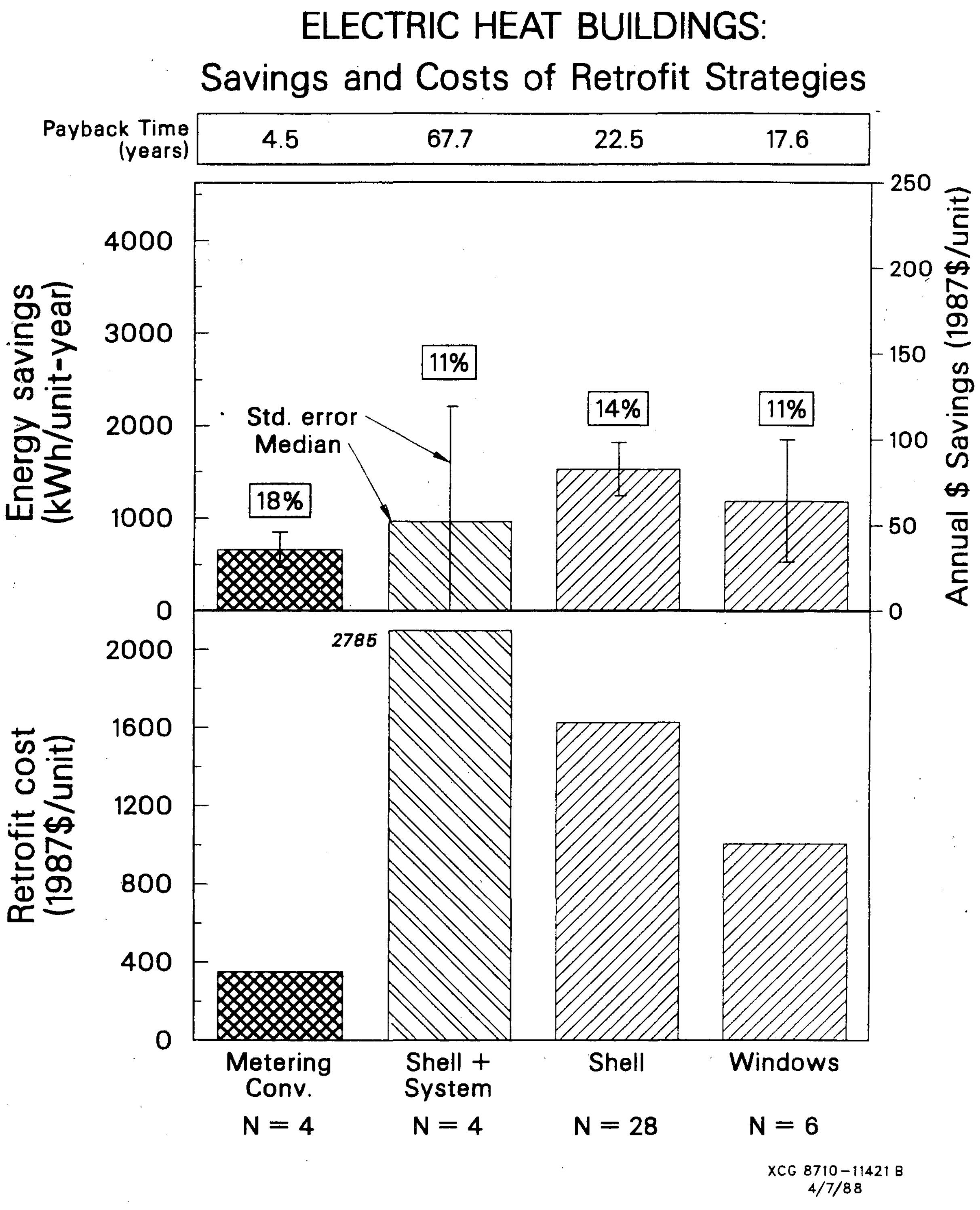

Fig. 6. Electricity savings, retrofit cost, and median payback time of various retrofit strategies in electric-heat multifamily buildings. The dollar value of electricity savings was calculated using the median electricity price (in 1987 $) from the sample of electric heat buildings ($0.054/kWh).

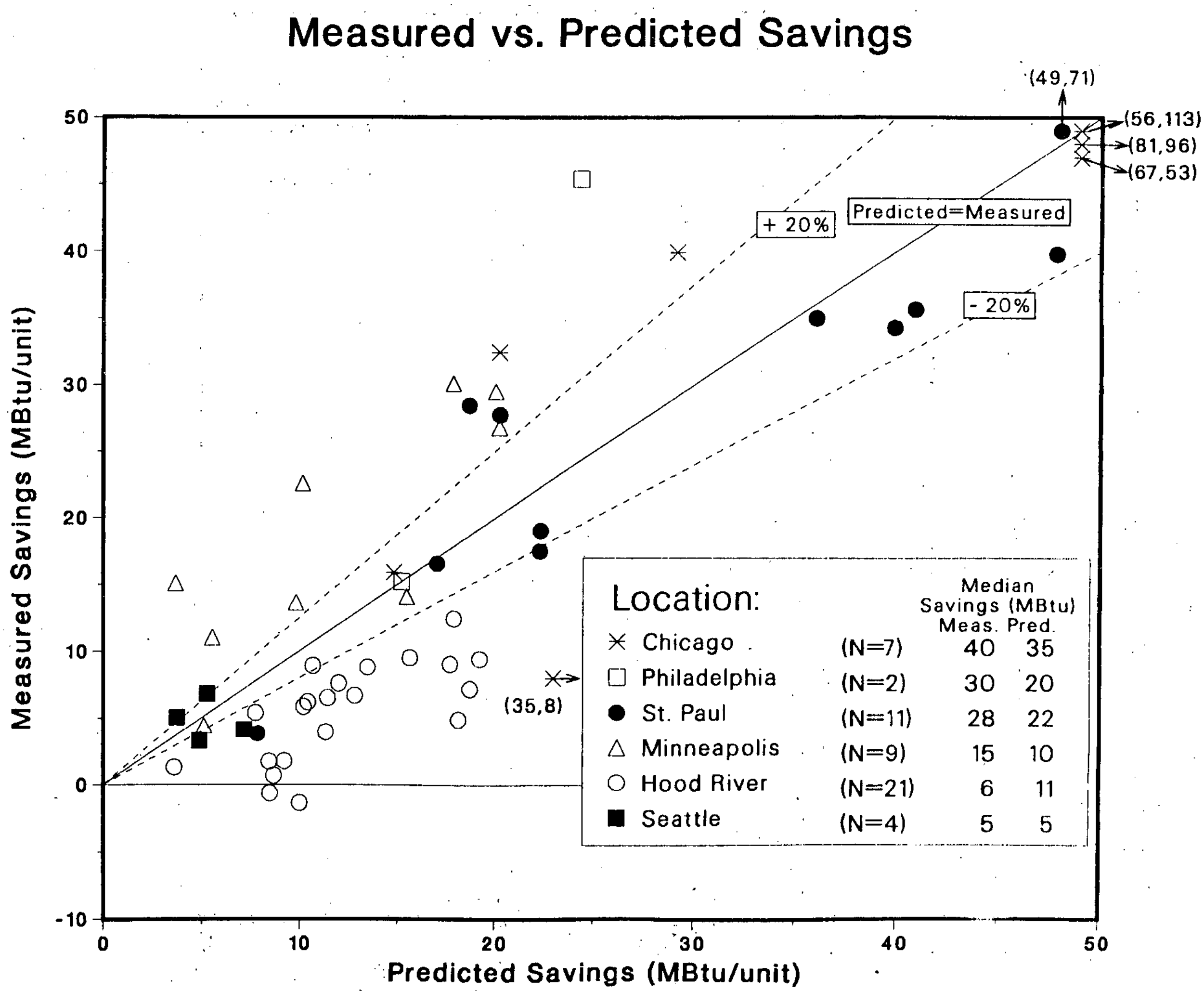

Fig. 7. Comparison of measured energy savings versus predictions for 54 projects, based on building energy audits and computer simulations. We also show median values for predicted and measured savings for groups of buildings that participated in six different retrofit programs: Hood River, Chicago Energy Savers Fund (CESF), St. Paul Energy Resource Center (ERC), Minneapolis Energy Office (MEO), Philadelphia Community Energy Development Corporation (CEDC), and Seattle City Light (SCL) Multifamily Pilot Program. CESF, Hood River, and SCL used steady-state heat loss engineering calculations to predict savings; CEDC and MEO used engineering estimates based on results from buildings retrofit with similar measures; ERC used building energy simulation models that calculated monthly building loads.

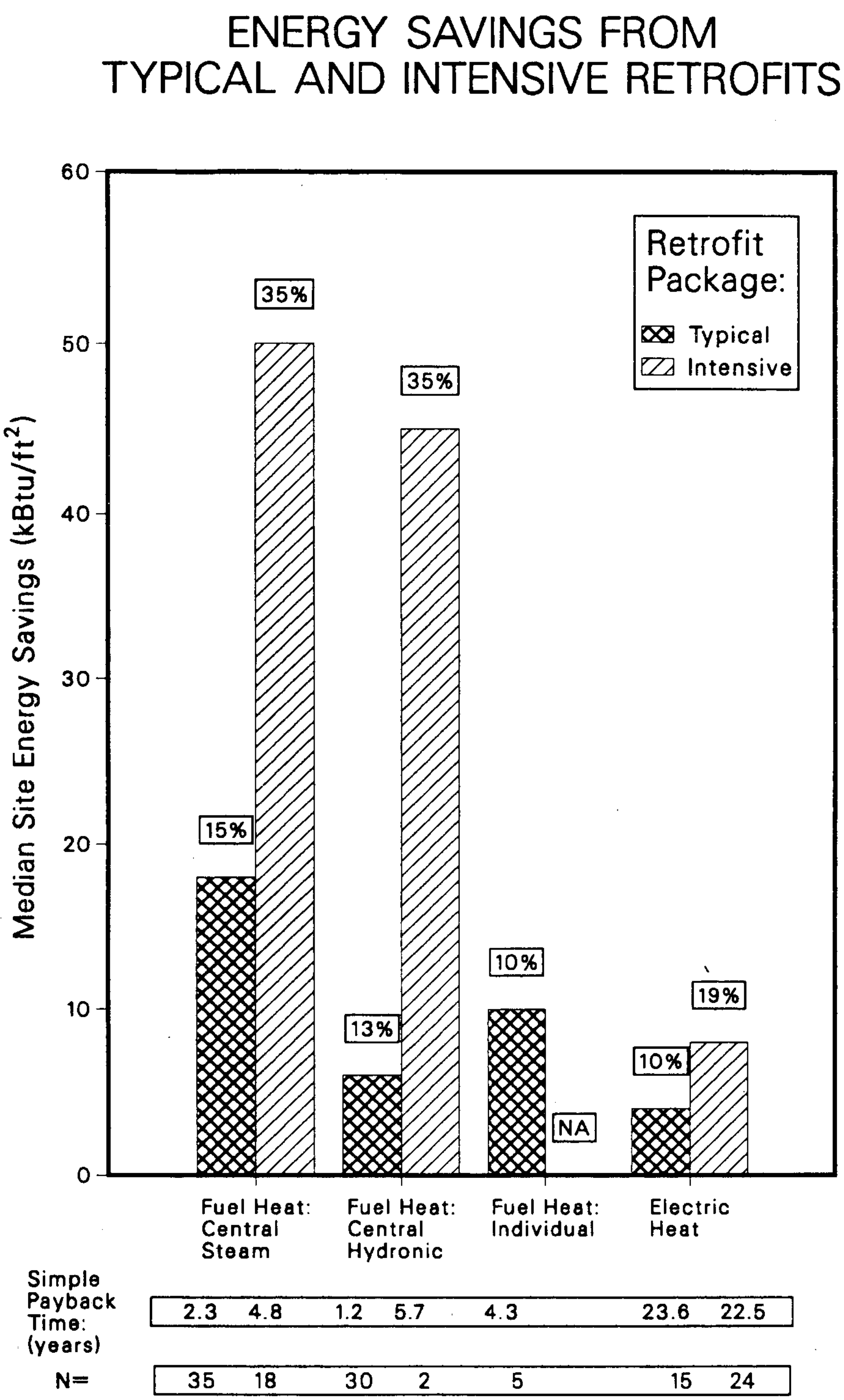

Fig. 8. Energy savings and cost-effectiveness of "typical" and "intensive" retrofits in our sample of multifamily buildings. Buildings are segmented by heating system equipment and space heat fuel because possible retrofit strategies and savings potential are strongly influenced by these physical characteristics. *Typical* retrofit packages reflect measures selected by private sector building owners based on their investment criteria under current market conditions (i.e., short payback times except for electric-heat buildings). *Intensive* retrofit packages are based on results from buildings that participated in weatherization programs that adopt a societal perspective in determining the level of investment and typically include some governmental or utility financial incentives.

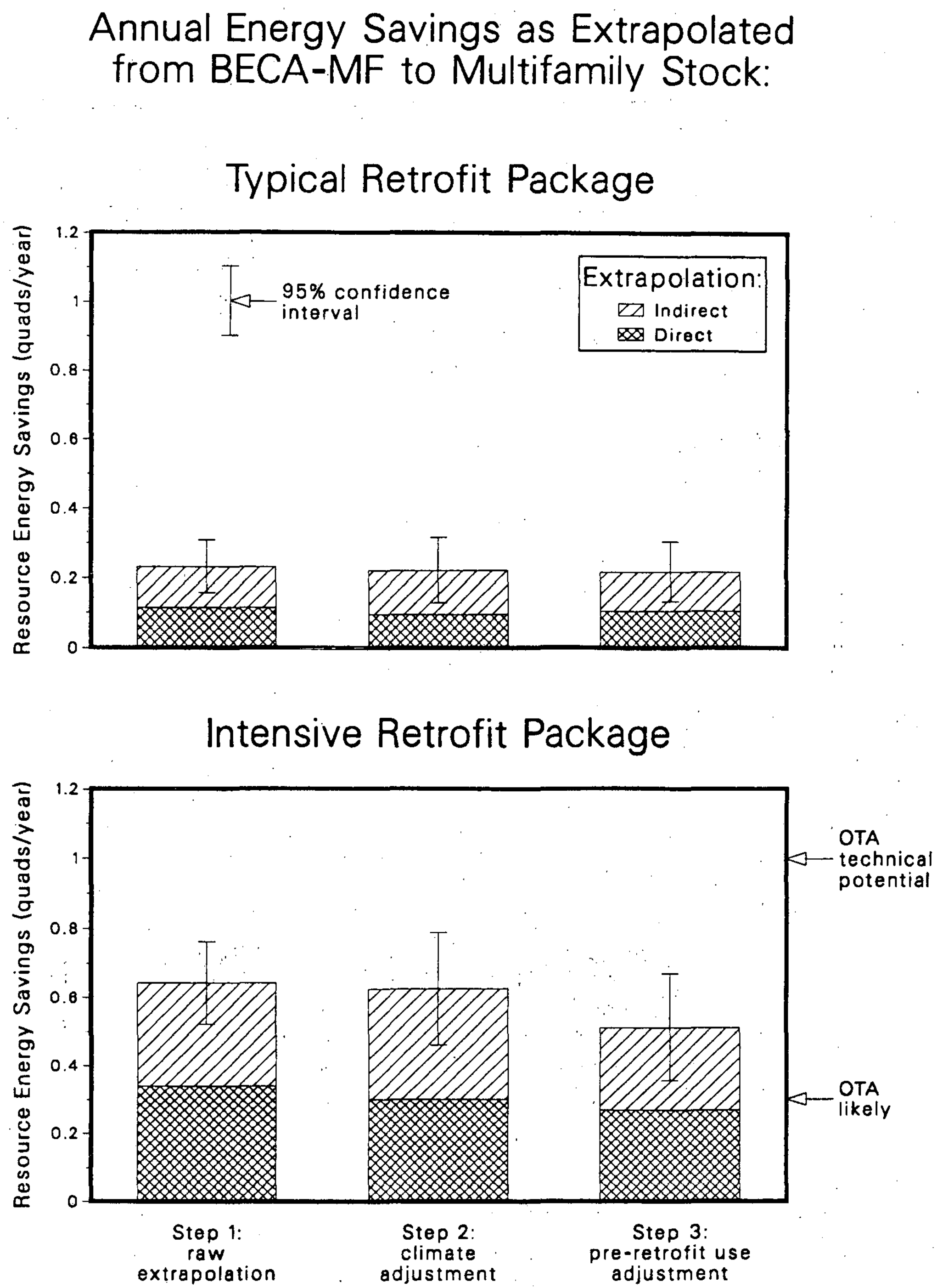

Fig. 9. Raw and adjusted nationwide estimates of savings potential are shown for "typical" and "intensive" retrofit packages. "Direct" extrapolation refers to the savings potential for 5+ unit buildings; savings for 2-4 unit buildings are shown as "indirect" extrapolation. Estimated technical and likely conservation potential are shown for comparison (OTA, 1982).

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