ANALYZING ENERGY CONSERVATION RETROFITS IN PUBLIC HOUSING: SAVINGS, COST-EFFECTIVENESS, AND POLICY IMPLICATIONS*

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ABSTRACT

Annual energy costs for the U.S.'s 1.2 million public housing units exceed one billion dollars. During the last decade, the U.S. Department of Housing and Urban Development (HUD) and local public housing authorities have initiated major conservation programs. Our review of energy conservation work in public housing indicated that in spite of substantial retrofit activity, little documented information is available on energy savings from retrofits. In this paper, we calculate energy savings and economic indicators for 43 retrofits, using consumption and cost data collected from case studies, housing authorities, and utilities. These results are compared with savings from conservation measures in privately owned, multi-family housing.

Heating system controls and window measures were the two most frequent retrofit strategies in the housing projects we examined. Median energy savings are 14% of pre-retrofit consumption, or 11.2 MBtu/unit-year; savings ranged from -7% to 62%. A median payback time of 12 years showed the retrofits, as a group, to be less cost-effective than a comparable sample of retrofit efforts in privately owned, multi-family buildings. We also examine the persistence of energy savings for a small sample of buildings for which we have several years of post-retrofit utility billing data; preliminary results suggest that proper maintenance is a critical factor in sustaining energy savings after temperature control retrofits in steam-heated buildings. Finally, we discuss qualitative factors that influence the acceptability of retrofits, including effects on comfort, building appearance, and security.

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INTRODUCTION

Approximately 3.4 million people live in the U.S. public housing system, whose 1.25 million units comprise close to 40% of all low-income, multi-family rental units, and 6% of all multi-family units (Perkins and Will, 1980; Harris, 1984). Annual energy expenses rose by 400% from 1970 to 1980 and currently exceed one billion dollars (U.S. Congress, 1984; Perkins and Will, 1980). This fuel bill now accounts for approximately 30% of the Department of Housing and Urban Development's (HUD) annual operating expenditures for public housing (Struyk, 1980). The rapid rise in energy costs is a key factor in the widening gap between building operating expenses and revenues, which are primarily derived from rents paid by tenants. This gap places an increasing strain on the operation and maintenance budgets of local housing authorities. During the last ten years, HUD initiated major retrofit programs to reduce energy consumption (and thus minimize rising energy expenses).

Although there has been major retrofit activity in public housing, little documented information is available on the measured energy savings from retrofits (Ritschard, 1985). In this study, we analyze utility bills from 38 public housing projects that implemented conservation retrofits. We briefly discuss key structural and institutional factors that are distinctive to public housing and that influence the potential for and analysis of energy savings. We also examine the persistence of energy savings for projects for which we have more than one year's worth of post-retrofit data, and discuss qualitative factors that influence the acceptability of retrofits.

WHY STUDY PUBLIC HOUSING RETROFITS?

Public housing exists in a quite different setting from that of privately owned multi-family housing. A review of the available data suggests that average energy consumption in the typical public housing unit (of 850 ft^2) is much higher than in existing multi-family dwellings.* A major study commissioned by HUD estimated annual site energy use for the average public housing unit at 146 MBtu/year (1 MBtu=10^6 Btu) (Perkins and Will, 1980). The average multi-family unit (817 ft^2) consumes only 77 MBtu/year, based on measured data from the Residential Energy Consumption Survey; this is 47% less than the public housing apartment (U. S. Congress, 1984).† Structural factors, such as vintage of the building, fraction of central heating, choice of heating fuel, and household size, explain some of the difference in consumption levels. For example, half of both public housing and multi-family units were built before 1960; however, very few public housing starts have occurred since 1975, while 15% of the multi-family units were built in the post-oil-embargo era, and, as a result, benefit from more energy-efficient construction practices. A higher fraction of public housing units have central heating systems than the existing multi-family stock (52 vs. 41%). The oil-heating share is roughly comparable for each sector (20-25%), although electric space heating is more prevalent in the multi-family stock compared to

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*Although some single-family dwellings are included in the public housing system, the vast majority of housing projects consist of multi-family buildings.

†The Residential Energy Consumption Survey is a representative sample of U.S. households, including those in public housing. The multi-family statistics cited here include both privately and publicly owned units; however, since public housing accounts for only 6% of multi-family units, we assume that the multi-family statistics primarily represent the characteristics of privately owned housing.

public housing (26 versus 7%), which tends to reduce site energy consumption for the sector (EIA, 1982 and 1984; Perkins and Will, 1980). The average number of persons per household is higher in public housing compared to the multi-family stock (2.9 compared to 2.3 persons per dwelling unit); household size is positively correlated with higher energy use for domestic hot water and cooking[*].

The institutional setting for conservation investments in public housing is an extreme example of one of the same barriers that hinders conservation efforts in private-sector multi-family buildings. Most public housing tenants have at least part of their energy consumption included in their rent payment; only 12% of public housing tenants pay for their own electricity, while 33% pay for their own gas (OTA, 1982). Hence, household energy consumption and energy expenditures are not directly linked. In contrast, almost half of the tenants in multi-family buildings have submetered consumption for at least one energy source (48% are partially or fully sub-metered) (EIA, 1982 and 1984). There is anecdotal evidence to suggest that public housing also tends to be less well-maintained than its private counterparts, which means greater losses through the building shell and lower heating system efficiency.

SOURCES OF DATA

We obtained information on retrofit projects from local public housing authorities (PHAs), HUD regional offices, and consultants who worked for local PHAs. We established data requirements based on analysis techniques used in the Buildings Energy Use Compilation and Analysis (BECA-B) project for existing residential buildings (Goldman, 1985). The data typically included metered energy consumption, installed retrofit measures and their cost, the price of the space heating fuel during the winter after retrofit, and a brief description of the physical characteristics of the buildings (e.g., conditioned floor area, building and heating system type).

We attempted to obtain data from major HUD-sponsored retrofit programs, including a $23 million program for 47 PHAs to modernize oil heating systems and a $5 million innovative energy conservation and solar grants program to 61 PHAs. However, comprehensive evaluations were available from only three of 61 PHAs (Trenton NJ, Greeneville TN, and St. Paul MN) that participated in the innovative energy grants program; these three projects are included in the database (Gold, 1982; TVA, 1984; Patten, 1982). We contacted the Office of Public Housing at HUD for information on the results of retrofit efforts in 14 other PHAs that had received grants, but were unable to obtain useful data.[†] Our experience with innovative energy grant recipients illustrates some of the difficulties in obtaining measured data on the results of conservation activities in public housing. Moreover, it indicates that, except for a few PHAs, a serious evaluation has not been conducted of HUD's early conservation initiatives.

We contacted many local PHAs directly, in an effort to determine the scope of their recent retrofit activity, evaluation of previous efforts, and current plans. This survey indicated that various retrofits had already been implemented at nearly all of the 40 PHAs surveyed (Ritschard, 1985). Twenty-eight retrofit projects conducted by four local housing authorities met the minimum data requirements: 14 projects managed by the New York City Housing Authority, 11 projects operated by the San Francisco Housing Authority, two projects in the Phillipsburg (NJ) Housing Authority, and one project run by the St. Paul Housing Authority. We also received retrofit data on public housing projects from Princeton's Center for Energy and Environmental Studies and the Tennessee Valley Authority (DeCicco, 1986; TVA, 1984). In addition, a private consultant (Chaim Gold) provided LBL with information on eight retrofits in New Jersey and Philadelphia.

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[*] Public housing density: The U.S. public housing system contains 1,173,000 units and 3,307,000 residents, and has a 2% vacancy rate, yielding an average density of 2.88 people/unit (Perkins and Will, 1980). Multi-family housing density: (EIA, 1982).

[†] We asked about PHAs that either had received a grant of significant size (greater than $75,000) or had installed heating or hot water system retrofits.

METHODOLOGY

The approach used in this study includes three principal elements: 1) normalizing energy use for weather and occupant effects, 2) analysis of the level and range of energy savings and identification of factors that are associated with savings, and 3) calculation of the cost-effectiveness of conservation investments. Retrofits are analyzed by *project*, which is the HUD term for a building or group of buildings located at one site and administered as one unit. Typically, the building(s) in a project are on one meter, and building characteristic data are compiled by HUD at the project level.

Changes in weather from year to year can mask the effect of a retrofit on energy consumption for a given building. For most of the projects, we used the Princeton Scorekeeping Method (PRISM) to adjust the weather-sensitive component of space heat fuel use. PRISM is an energy analysis model that regresses energy use versus daily average temperatures to find the weather-normalized annual consumption (Fels, 1986).

Energy use of the space heat fuel at each project was normalized by the number of apartment units so we could compare energy use on a per-unit basis. We found that occupant turnover was high in some public housing projects, especially those that were poorly maintained or mostly occupied by families, and occupancy rates varied greatly over time. Hence, we divided energy use by the average number of *occupied* units during each of the pre- and post-retrofit periods (when data were available) to account for the effects of changing vacancy rates on energy consumption levels.

Labor and materials costs at the time of retrofit were converted to constant dollars (1985 $), and we calculated two economic indicators: simple payback time (SPT) and internal rate of return (IRR).[*],[†] Conservation investments are amortized over the measures' expected physical lifetimes and estimated annual operation and maintenance costs are added to the initial investment.

The economic analysis assumes that one entity, either a local housing authority or HUD, paid for and received all benefits and costs associated with a retrofit. In fact, the actual distribution of benefits and costs between the various parties is much more complex and is as dependent on the financing arrangement as on the actual dollar value of the energy savings (Mills et al., 1986). Therefore, the economic indicators calculated in this paper do not represent the actual benefits to the housing authority or to HUD; they are included only to facilitate *comparisons* of the measures' cost-effectiveness. It is worth noting that roughly one-third of the retrofit projects included in this study were implemented through demonstration programs or relied heavily on the existence of tax credits; hence cost-effectiveness was not always the dominant consideration in retrofit selection.

RESULTS

Building Characteristics and Retrofit Measures

The public housing projects in this study include most building types found in the residential sector, from single-family dwellings to 1000-unit apartment complexes, although low- and high-rise multi-family dwellings predominate. Our sample has a regional bias, as projects are concentrated principally in the New York-New Jersey area and in California. Ninety percent of the projects in the data base are located in the Northeast or California, compared to 40% of the public housing stock. Retrofit data for PHAs in the Midwest and South are particularly lacking.

This compilation of retrofit activity in public housing is not intended to be representative of the entire stock, although comparison of characteristics of retrofitted buildings with stock averages offers some indication of the applicability of our results (Table I). Almost 90% of the projects in the database have

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[*] The internal rate of return is the rate of interest which causes the discounted life-cycle costs and savings from an investment to be equal. The IRR should be equal to or greater than the return available through investment in the market.

[†] An energy escalation rate of 4%, representing the accepted figure at the time of most of the retrofits, is used in the economic calculations.

central heating systems, and over 50% heat with oil. In contrast, gas is the principal space heat fuel in the public housing stock, and the stock is evenly split between central and individual unit heating systems. Of the centrally heated projects in the database, 19% have hydronic (hot water) distribution and 25% have steam distribution systems.

Retrofit strategies focused principally on reducing consumption for space heat and domestic hot water, the two largest end-uses. Table II shows the frequency with which different retrofit measures were installed in the 38 projects. (In most cases, more than one measure was installed at a project.) Retrofitting existing heating systems with improved controls was most popular, with first costs ranging from $100-450/unit. Examples of measures included in this category are thermostatic radiator vents, boiler aquastats, outdoor resets and cutouts. Window measures were also popular. For example, the New York City Housing Authority installed double-glazed, thermal-break aluminum windows in nine apartment complexes. This retrofit was fairly expensive, averaging $1070/unit in the nine buildings. Retrofits to reduce domestic hot water energy use were also common. The San Francisco Housing Authority installed solar domestic hot water systems at six projects, and wrapped hot water tanks at two other projects, while several Northeast housing authorities installed separate domestic hot water boilers. Retrofit costs ranged from $10 to almost $20,000 per unit among projects in this study; the median first cost was approximately $550/unit.

Energy Savings

Median annual resource energy savings were 11.2 MBtu/unit, or 14% of pre-retrofit consumption. Savings varied widely, ranging from -7% to 62%. Energy savings show some correlation with consumption prior to the retrofit (r=0.52) (Fig. 1). Projects in cold (>4500 HDD) climates have a median pre-retrofit consumption of 108 MBtu/unit, while those located in milder regions use about 57 MBtu/unit. Median savings within each climate zone are similarly split: projects in cold regions saved about 14 MBtu/unit, compared to 4 MBtu/unit in mild areas. However, good management practices can overcome the influence of climate at specific properties. For example, most projects in New York and Minnesota (over 4800 HDD/year) use less energy than some of the California and Tennessee buildings (under 3900 HDD/year). In these projects, other factors such as previous retrofit activity, building types, heating systems, operating practices, and occupant behavior must have a stronger influence on pre-retrofit energy consumption than climatic variation.

Our results suggest that the type of measure selected has the greatest effect on the level of energy *savings*. Groups of similar retrofits are compared in Table III. Heating controls and energy management systems produced significant energy savings (17-26 MBtu/unit), and had paybacks under five years. Window replacements and retrofits saved from 5 to 16 MBtu/unit, but had payback times in excess of 12 years because of high capital costs. High-efficiency, modular, condensing-pulse combustion boilers and an incandescent-to-fluorescent lighting conversion were particularly cost-effective (with payback times around one year), although results should be interpreted very cautiously as we have only one example of each of these retrofits.

We have five examples of housing authorities that installed similar retrofits at more than one project (Fig. 2). In some cases, we can identify structural factors that account for a fraction of the observed variance in savings resulting from similar retrofits. For example, in San Francisco, five buildings received various shell measures (attic insulation, caulking and weatherstripping) and low-cost hot water retrofits (e.g., low-flow showerheads and heater blanket insulation). The projects with the highest per unit energy usage before the retrofits were installed also had the largest savings in relative and absolute terms. The project with the highest pre-retrofit usage also had improperly functioning heating system controls (e.g., time clocks were inoperable on several boilers and a number of room radiators with manual control valves were stuck in the open position).

We also have data on solar domestic hot water systems in San Francisco that were installed at six senior projects which are similar to each other in construction type and vintage. Variability in savings may be explained in part by the configuration that was required for each solar retrofit. For example, the three buildings with no energy savings had long pipe runs (and presumably greater standby losses) compared to the buildings with consumption reductions.

At the 9 New York City Housing Authority (NYCHA) apartment complexes that received window retrofits, energy savings and pre-retrofit consumption are fairly uniform, compared to the other groups of buildings. NYCHA has an extensive and long-standing energy management program with a national reputation. Elements of their program include: 1) installation of a computerized monitoring system for fuel oil consumption with baseline consumption data, objectives for fuel savings, and performance indicators to measure progress; 2) training programs to enhance technical skills of maintenance staff; and 3) systematic implementation of heating system efficiency improvements and building envelope retrofits based on detailed building audits (NYCHA, 1983). The uniform consumption levels at the buildings retrofitted with double-paned, thermal break windows is attributable, in part, to the effects of the several sets of retrofits that the buildings had already received.

Persistence of Savings

The effective life of a retrofit can be drastically shortened by lack of maintenance or improper operation. Most housing authorities do not track energy savings for more than a year after retrofit; however, we were able to obtain two or more years' worth of post-retrofit energy use data for five retrofits. Of these five, the two Trenton projects received heating system retrofits; attic insulation, caulking/weatherstripping, low-flow showerheads, and water heater blankets were installed at the three San Francisco projects. (We will refer to this group of retrofits as "shell" measures, since the attic insulation accounted for the bulk of costs, and presumably, of savings.) Figure 3 shows the normalized annual consumption before and after retrofit at each of these projects. Among these buildings, first-year energy savings have been more stable over time in the projects that installed shell measures compared to the projects with heating control retrofits. Post-retrofit energy use has remained constant at the Sunnydale and Potrero Terrace projects although, at Alemany, consumption has again increased to pre-retrofit levels even after adjusting for weather and the number of occupied units.

First-year energy savings were dramatic at the Campbell and Kerney projects (22 and 31%) after boiler replacement and heating control installation. However, energy use increased substantially at both projects during the second year after the retrofit, reclaiming one-tenth of the first-year savings at Kerney and one-half of the savings at Campbell. At Campbell Homes, where a third year of data was available, energy savings continued to decrease, with energy use at 92% of pre-retrofit levels. Anecdotal evidence suggests that the deterioration in energy savings at Kerney and Campbell results from inadequate maintenance, a crucial factor in older steam-heated buildings (Gold, 1985). Sufficient operating budgets and a skilled maintenance staff appear necessary to insure the persistence of initial energy savings obtained from heating system control retrofits in steam-heated buildings. HUD operating budget cutbacks hinder local housing authorities' efforts to maintain their buildings. This situation makes it difficult to recommend and implement cost-effective heating system retrofits, because energy savings over time are dependent on regular maintenance.

Combining Retrofits with Rehabilitation

During the last decade, most retrofit investments in public housing have been financed by HUD modernization funds, which have been traditionally used for heating plant replacements and major structural rehabilitation. A major study sponsored by the Office of Technology Assessment concluded that housing rehabilitation programs offer an excellent opportunity to make energy investments in housing when other alterations are being made and access to the structure is easier; conservation investments improve program cost-effectiveness and overall building value (Naismith, 1984; Perkins and Will, 1980). In many cases, the incremental costs of conservation features are minor compared to rehabilitation expenses, so operating expenses are reduced in return for a minimal investment. This strategy is particularly appropriate for the public housing sector, which has approximately 90,000 "chronic problem" units (i.e, buildings that are physically deteriorating and have problems with vandalism, inadequate maintenance, and poor management) that would require repair before energy conservation measures could be implemented (Perkins and Will, 1980).

A small fraction of the buildings in this study had retrofits installed as part of a larger rehabilitation effort (Table IV). Two low-rise projects in Phillipsburg NJ, which underwent extensive rehabilitation between 1980 and 1983, are good examples of retrofit/rehabilitation possibilities. Energy use decreased drastically at both projects in the year following the rehabilitation work: normalized annual consumption (NAC) declined by an average of 47%. Major structural renovations included a new exterior facade and roof, thermopane windows, wall, roof, and crawl space insulation, maximum set thermostats, and replacement of doors and storm doors. In addition, the centrally heated project (General Rehab #1) received new boiler valves and controls; gas warm-air furnaces were replaced in each of the units at the second project.

The Trenton Housing Authority used several approaches when it had to replace boilers in four of their low-rise projects. At three sites, they replaced the existing boilers with similar new equipment plus improved heating controls. (These are the same projects discussed in the sections on range and persistence of savings.) First-year savings at these projects ranged from 10 to 54 MBtu/unit. At one project, high-efficiency, modular, condensing-pulse combustion boilers were installed. The incremental expense (over the cost of replacement with ordinary boilers) of the high-efficiency boilers was $550/unit (1985 $). The large energy savings--50%--resulting from the installation repaid the incremental expense in less than one year.

The six examples discussed here are but a preliminary investigation into the energy-saving possibilities of combined rehabilitation/retrofit. The conservation opportunities present in rehabilitation work are typically not quantified since housing authorities often cannot provide data on the incremental costs of the conservation measures. However, combining efficiency investments with rehabilitation clearly gives housing authorities the opportunity to lower long-term operating costs, at a cost that is small compared to the overall rehabilitation costs.

DISCUSSION

Data Limitations

The energy consumption data collected in many public housing projects are often of uneven quality. The most common problems were associated with the typical configuration of utility metering systems (i.e., project-level rather than individual building or apartment meters) and, for oil-heated buildings, limitations in using fuel oil delivery data (e.g., unrecorded deliveries, large tank size, and more frequent readings in the heating season, all of which make it difficult to determine actual oil consumption use patterns). Retrofits that affected only some of the buildings at a project cannot be analyzed when the entire project is on one meter. In many cases, data on vacancy rates and number of occupants were not available. In addition, usage could decrease/increase because of changes in building operating conditions which may or may not be associated with the retrofits (we are most knowledgeable about operating practices for projects located in San Francisco, Trenton and Asbury Park).

Comparison with Results from Privately Owned Buildings

In general, we find that there is a greater range of energy savings and cost-effectiveness in public housing projects than in a sample of retrofitted, privately owned, multi-family buildings (Goldman, 1986a). Median percentage savings are approximately the same for the two groups of buildings (15%), although the median payback time for the privately owned buildings was much shorter than that of public housing (3 vs. 12 years). The difference in cost-effectiveness can be explained in part by the fact that many public housing retrofits were part of demonstration projects, which by definition are not uniformly successful. For example, both highly successful computerized energy management systems and poorly designed solar space heat systems that required occupant operation were funded under HUD demonstration programs.

Qualitative and Other Impacts

We also have anecdotal and some survey data on the qualitative impacts of a few of these retrofits. In general, public housing tenants were most concerned with comfort, building appearance, and security. Housing Authority managers in San Francisco said that tenant complaints about insufficient heat caused them to disable boiler time clocks that regulated the space heat water circulation pump, so the pump would run for 14 rather than 24 hours a day (Goldman, 1986b). In contrast, NYCHA officials reported that tenants felt that thermostatic radiator valves installed in four projects resulted in more even distribution of heat, thus improving comfort.

Trenton housing officials indicated that storm window retrofits were popular because tenants felt that it improved the overall appearance of the project. NYCHA staff also cited other positive impacts from the replacement of steel casement windows with double-glazed thermal break aluminum windows. The original windows were leaky (leading to excessive air infiltration), required substantial amounts of maintenance, and were frequently subject to glass breakage during windy weather. The Housing Authority estimated that the new windows reduced operation and maintenance costs by $30,000/year for a typical 1000-unit complex (NYCHA, 1983).

The Trenton Housing Authority had to consider some unexpected side effects after the installation of modular condensing-pulse combustion boilers at one of its projects. The high-efficiency boilers produced a great deal of noise (Gold, 1985). Fortunately, the boilers are located in a separate building far from the residences. This equipment would not be favorably received if installed in a basement boiler room near living quarters. Although information of this sort is often anecdotal, in some cases it can help building owners become aware of possible adverse effects prior to installation of similar retrofits.

CONCLUSIONS

We stress that the retrofits studied here are selected examples of conservation efforts within the public housing system, intended to give an idea of the possibilities of conservation and the experiences of individual PHAs. Analysis of our sample of 43 retrofits shows that conservation work has produced significant energy savings in the public housing sector, but the effort has not always been cost-effective. A large number of expensive retrofits were carried out under demonstration programs, with mixed results. Preliminary results suggest that proper maintenance is a critical factor in sustaining energy savings after temperature control retrofits in steam-heated buildings. In addition, qualitative factors such as a measure's effect on comfort, building appearance, and security reportedly have a strong influence on a retrofit's acceptability, and therefore, its success.

This study represents an initial effort to summarize measured data on retrofit efforts in public housing. During this project, we have gained a thorough appreciation of the difficulties in evaluating public housing conservation retrofits. We believe that many local housing authorities and HUD still do not see the potential benefits that can be derived from an evaluation of the actual field performance of conservation strategies. Documenting measured savings requires that local housing authorities pull together historical energy use, occupancy, and economic and building characteristic data in a systematic fashion. Initiation of this process alone produces the necessary information for a crude energy management accounting system (à la NYCHA), and provides the basis for local PHAs to track energy use patterns and to set objectives for reasonable consumption levels so they can begin to regain control over their energy expenses.

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REFERENCES

J. DeCicco, G. Dutt, D. Harrje, and R. Socolow, "PRISM applied to a multifamily building: Lumley case study," *Energy and Buildings,* 9:1, 1986.

Energy Information Administration (EIA), *Residential Energy Consumption Survey: Housing Characteristics 1980,* DOE/EIA-0314, Washington, D.C., June 1982, p. 21,37.

Energy Information Administration (EIA), *Residential Energy Consumption Survey: Housing Characteristics 1982,* DOE/EIA-0314(82), Washington, D.C., August 1984, p. 35,37.

M. F. Fels, "The Princeton Scorekeeping Method: An Introduction." *Energy and Buildings,* 9:1, 1986.

C. S. Gold, "The Page Homes demonstration project for the application of computers to energy conservation in public housing authority projects," Trenton, NJ, February 1982.

C. S. Gold, "Retrofit Technology," Conference of Practitioners in Multi-Family and Rental Housing Energy Conservation, Philadelphia, PA, February 11-13, 1985.

C. A. Goldman, "Measured Energy Savings from Residential Retrofits: Updated Results from the BECA-B Project," *Energy and Buildings,* 8:2, 1985, p. 137-155.

C. A. Goldman, "Energy Savings in Retrofitted Multifamily Buildings: New Results from the BECA-B Project", *Proceedings of the ACEEE 1986 Summer Study,* Santa Cruz, CA, 1986.

C. A. Goldman and R. L. Ritschard, "Energy Conservation in Public Housing: A Case Study of the San Francisco Housing Authority", *Energy and Buildings,* 9:1, 1986.

J. Harris and C. Blumstein, editors, *What Works: Documenting Energy Conservation in Buildings,* American Council for an Energy-Efficient Economy, Washington, D.C., 1984, p. 65.

E. Mills, C. A. Goldman, and R. L. Ritschard, "Analysis of the Financial Impact of Energy Conservation Investment Strategies in Public Housing," *Proceedings of the ACEEE 1986 Summer Study,* Santa Cruz, CA, 1986.

N. C. Naismith, "Building Energy and Equity: Back to the Drawing Board", *What Works: Documenting Energy Conservation in Buildings,* ed. Jeffrey Harris and Carl Blumstein, American Council for an Energy-Efficient Economy, Washington, D.C., 1984, p. 451.

New York City Housing Authority Department of Research and Policy Development (NYCHA), "New York City Housing Authority Energy Management Report", NYCHA Office of Public Information, New York, NY, 1983, p. 6,9.

Office of Technology Assessment (OTA), *Energy Efficiency of Buildings in Cities,* Washington, D.C., March 1982, p. 154.

C. Patten, M. Sherman, and B. Shapiro, "Case Studies of Successful Energy Conservation Programs in PHAs: St. Paul, Minnesota," Council of Large Public Housing Authorities, Boston, MA, December 1982.

Perkins and Will and the Ehrenkrantz Group, *An Evaluation of the Physical Condition of Public Housing Stock: Final Report,* H-2850, U.S. Department of Housing and Urban Development, March 1980, volume 1: p. 9,13,14,147,163,164; volume 4: p. 109,159.

R. Ritschard, C. Goldman, E. Vine, R. Diamond, E. Mills, and K. Greely, "Federally-Assisted Multi-Year Research Plan", LBL-19683, Lawrence Berkeley Laboratory, October 1985, p. 11-14,A-1,A-2.

Tennessee Valley Authority Solar Applications Branch (TVA), "Greeneville Passive Solar Retrofit Demonstration," TVA/OP/ECR-84/62, Knoxville, TN, 1984.

R. J. Struyk, *A New System for Public Housing: Salvaging a National Resource,* The Urban Institute, Washington, D.C., 1980, p. 64.

U.S. Congress, House Subcommittee on Housing and Community Development of the Committee on Banking, Finance, and Urban Affairs, "Testimony of Henry C. Kelly," *Review of Federal Policies and Building Standards Affecting Energy Conservation in Housing,* 98th Congress, 2nd session, #98-85, (March 21 and 22, 1984), p. 7,9.

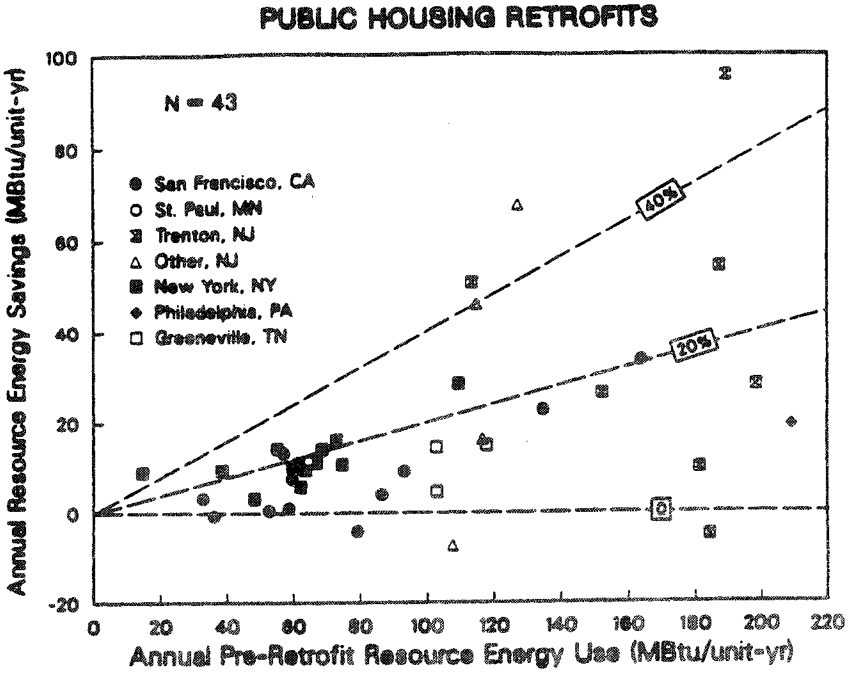

Fig. 1. Energy savings as a function of pre-retrofit consumption. Savings are somewhat correlated with pre-retrofit energy use (correlation coefficient=0.52). Electricity consumption is converted into resource energy, using 11500 Btu/kWh.

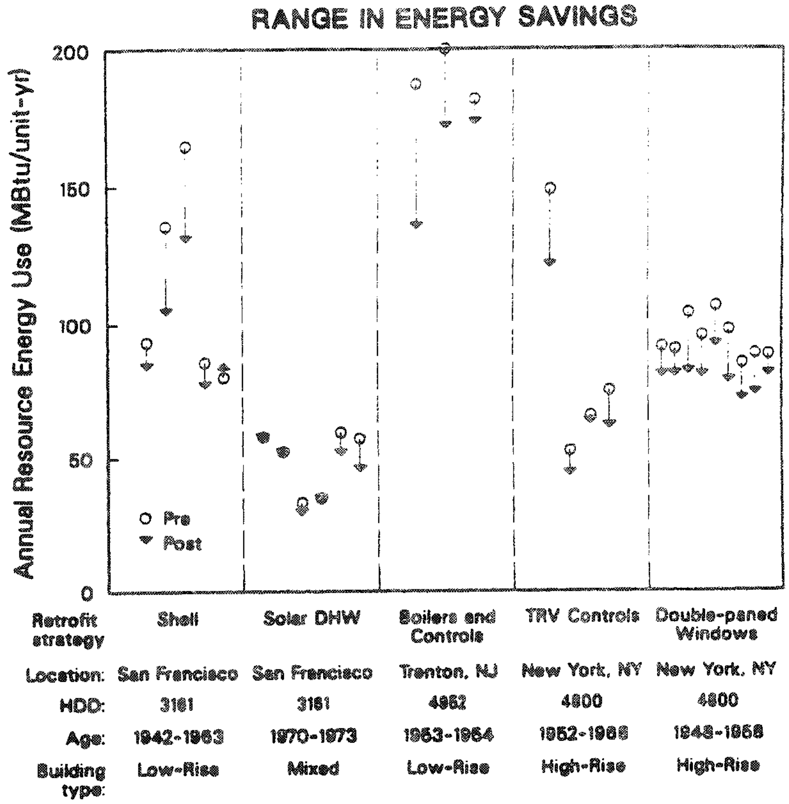

Fig. 2. Range in pre- and post-retrofit consumption among similar retrofits carried out at different projects. "Shell" measures include attic insulation, weatherstripping, and low-cost domestic hot water retrofits. "Solar DHW" refers to active solar domestic hot water systems. "TRV Controls" are thermostatic radiator valves. Consumption at the San Francisco projects includes energy used for space heat, domestic hot water, and cooking; the oil-heated projects in Trenton and New York include space heat and (estimated) domestic hot water use only.

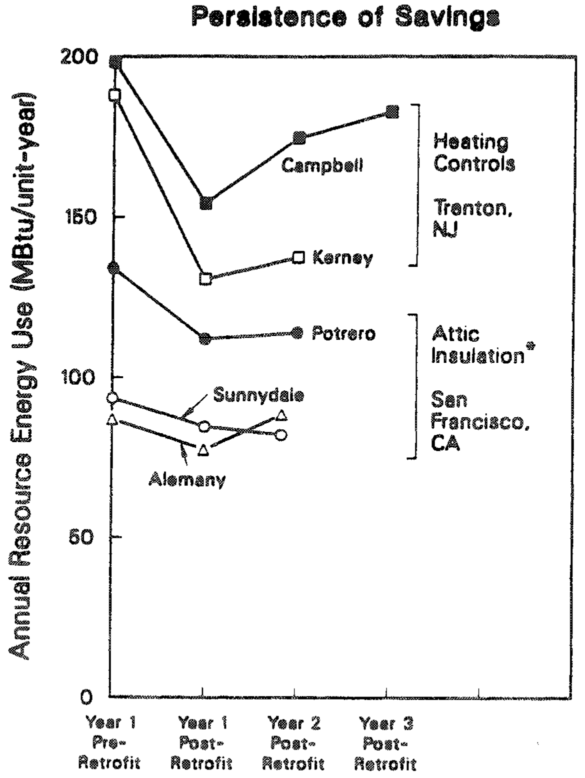

Fig. 3. Persistence of savings for projects with multiple years of post-retrofit data. Energy use increases after the first post-retrofit year at the Trenton projects; energy savings are sustained through both post-retrofit years at two of the three San Francisco projects.

*Other low-cost measures, including caulking & weatherstripping, low-flow showerheads, and domestic hot water blankets, were also installed at these projects.

Table I. Characteristics of retrofitted projects.

Building Characteristic		% of Projects in Data Base	% of Public Housing Stock[a]
Building Type:	High-Rise[b]	47	30
	Low-Rise	47	70
	Combined	6	--
Occupant Type:	Family	58	46
	Senior	22	33
	Mixed	6	21
	Unknown	14	--
Heating Plant:	Central	89	51
	Individual Unit	8	49
	Unknown	3	--
Space Heat Fuel:	Gas	37	68
	Oil	54	25
	Electric	3	7
	Mixed	6	--

[a] Percentage of projects as estimated in Perkins & Will and the Ehrenkrantz Group, *An Evaluation of the Physical Condition of Public Housing Stock: Energy Conservation*, H-2850, (U.S. Department of Housing and Urban Development, March 1980), volume 4, p. 109.

[b] High-Rise = 5 stories or more.

Table II. Types and costs of retrofits.

Retrofit Type	Number of Retrofits
Envelope:	
Attic Insulation	6
Caulk & Weatherstrip	6
Window Management	3
Window Replacement	10
Heating System:	
Heating System Replacement	5
Heating System Retrofit	2
Heating Controls	14
Energy Mangement Systems	3
Solar Space Heat	2
Operations & Maintenance	1
Domestic Hot Water System:	
Separate DHW Heater	5
Solar DHW	6
Lighting:	
Lighting Controls	1
Lighting Replacement	1

Initial Retrofit Cost (1985 $/unit)	Number of Retrofits
< $250	10
$250-500	6
$500-1000	9
$1000-1500	5
$1500-2000	5
> $2000	3

Table III. Savings and cost-effectiveness by retrofit strategy.

Retrofit Strategy	Number of Projects	Number of Units	Mean Resource Energy Savings (MBtu/unit-yr.)	(%)	Mean SPT (years)	Mean IRR
High-Eff. Boilers[a]	1	112	95.4	50	0.8[b]	1.30[b]
CEMS[c]	3	1192	26.2	25	2.8	0.50
Heating Controls	6	1539	16.8	18	4.8	0.25
Solar Space Heat	2	77	9.6	9	169.8	0.00
Windows[d]	11	11261	9.2	14	18.2	0.08
Lighting	1	159	9.1	71[e]	1.4	0.87
Solar DHW	6	388	4.2	8	73.3	0.01

[a] High-Efficiency Boilers=Replacement of central boilers with high-efficiency, modular, condensing-pulse combustion boilers.

[b] Based on incremental cost over replacement with regular boilers.

[c] CEMS=Computerized energy management systems.

[d] Windows=thermal-break, double-pane windows (9 projects); single-pane (1 project); insulated shades (1 project).

[e] Percentage of pre-retrofit *lighting* consumption only.

Table IV. Savings and costs for rehabilitated buildings.[a]

Retrofit	No. of Units	Pre-Retrofit Consumption (MBtu/unit)	First Year Savings (MBtu/unit)	(%)	Total Cost (1985 $/unit)
Phillipsburg, NJ:					
General Rehab #1[b]	150	166.2	67.5	41	13767
General Rehab #2	222	127.3	67.4	53	12766
Trenton, NJ:					
Boiler & Controls #1[c]	102	187.5	53.8	29	2039
Boiler & Controls #2	81	198.6	27.9	14	3818
Boiler & Controls #3	219	181.7	9.8	5	1556
High-Efficiency Boilers[d]	112	189.4	95.4	50	1776

[a] All projects consist of low-rise buildings.

[b] "General Rehab" refers to extensive renovations, including a new insulated facade and roof, thermopane windows, insulated doors and storm doors, crawl space insulation, new boiler controls and valves, and maximum set thermostats at #1, and an insulated facade, thermopane windows, new doors and storm doors, maximum set thermostats, and replacement of individual-unit gas furnaces at #2.

[c] "Boilers & Controls" refers to replacement of central boilers with similar new boilers plus heating controls. Because boiler costs do not scale linearly with the number of dwelling units, the costs per unit for this measure varies widely.

[d] "High-Efficiency Boilers" refers to replacement of central boilers with high-efficiency, modular, condensing-pulse combustion boilers.