DHW ENERGY SAVINGS IN MULTIFAMILY BUILDINGS

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ABSTRACT

Field studies and energy consumption analyses of domestic hot water (DHW) system retrofits were performed on seven multifamily building complexes in Trenton and Asbury Park, New Jersey. The retrofits all involved substitution of separate gas-fired water heating equipment for existing systems, all of which used central space-heating boilers to heat the water. Only one of the new systems consists of water heaters in each apartment; the rest are centrally based. The measurement of energy savings from these retrofits posed special problems which precluded the direct use of a standard scorekeeping methodology such as PRISM (The PRInceton Scorekeeping Method). Some of the problems were: oil-heated buildings where tanks are not filled during deliveries, oil to gas equipment conversion, lack of DHW fuel submetering, concurrent heating system retrofits, seasonal changes in DHW heating equipment, and changes in gas meter configuration before and after retrofits. Since some of these situations are quite common, the methodology developed to handle them will have broad applicability. The results show great variation in savings across buildings, ranging from -15% to +8% for the five buildings for which annual savings were determined. The three buildings with positive savings also report an inadequate supply of hot water following the retrofit. The lack of savings is a surprising result, since the installation of a water heater separate from the heating system is a popular measure generally believed to have significant energy savings potential.

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INTRODUCTION

Domestic hot water (DHW) comprises the second largest use of energy in houses next to space heating, and can be an even greater part of the total in multifamily buildings. DHW heating equipment in multifamily buildings is often mechanically quite different from that in houses, and may involve continuously circulating distribution loops, long runs of underground piping, and higher storage temperatures. DHW system retrofits are becoming common and range from piping repair and reinsulation to complete replacement of DHW heating equipment.

The purpose of our study is to quantify the energy savings due to major DHW system retrofits in seven multifamily buildings, and in the process, to develop methods for analysis which have broad applicability. Data of this type should improve decision making for managers of modernization programs in multifamily buildings.

The buildings in our study are all New Jersey public housing projects, five in Trenton and two in Asbury Park. Building characteristics are summarized in Table I. The buildings range in construction date from 1939 to 1963, and in style from multi-building walk-ups to single building high-rise. They range in size from 60 to 376 units. All are family housing with the exception of Lumley Homes, which is for senior citizens.

The five Trenton properties are heated with paired, oil-fired steam boilers which, before the retrofits, also provided DHW by means of heat exchangers. DHW and steam are distributed among the buildings by underground piping. The retrofits made in these properties were fairly conventional and virtually identical. Each consisted of removal of the existing heat exchangers and the installation of atmospheric-combustion commercial water heaters, storage tanks, mixing valves, and controls. The number of heaters installed varied by property from two to four, and either one or two storage tanks were installed.

The control systems on the new units are fairly straightforward. Water is circulated through the heaters and tank(s) by a pump which is controlled according to a temperature sensor in the top of the tank. The burners are each on or off independently according to the outlet temperature at each heater. As in the old systems, a thermostatically controlled pump circulates hot water so that it is available at all locations without delay. Return water enters at the bottom of the tank(s) and leaves at the top where it is mixed with cold water in a three-way valve which operates to maintain a fixed hot water supply temperature. The loop circulator is actuated by a temperature sensor on the return line, as it was before the retrofit. All of the temperature setpoints are adjustable and have about a 10F dead-band.

The Trenton systems were installed from October 1985 to January 1986, and ranged in cost from $190 to $340 per apartment.

Hot water at Asbury Park Village and Lumley Homes was previously provided by centrally-located gas-fired steam boilers, heating storage tanks (1000 gal. at APV, 865 gal. at Lumley) with heat exchangers. The distribution systems were similar to those in Trenton. At Asbury Park Village, individual gas-fired water heaters were installed in each apartment, along with furnaces, in September 1983 at a cost of $700/apt[1] (December 1985 dollars) (Dutt et al., 1986). At Lumley homes, a separate steam boiler for summertime water heating was installed in May 1982 at a cost of $191/apt (December 1985 $) (DeCicco and Dutt, 1986).

METHOD FOR ENERGY ANALYSIS

In this section, we discuss briefly the circumstances which precluded the direct use of a standard scorekeeping method such as PRISM in estimating DWH retrofit energy savings. Some of the problems were: oil heated buildings where tanks are not filled during deliveries, oil to gas equipment conversion, lack of DHW fuel submetering, concurrent heating system retrofits, seasonal changes in DHW heating equipment, and changes in gas metering configuration before and after retrofits. The models developed to handle these cases will be explained below.

PRISM

PRISM, the PRInceton Scorekeeping Method, uses utility bills to determine a weather-adjusted index of annual energy use called normalized annual consumption (NAC) (Fels, 1986). The weather in the normal year is characterized by the annual heating degree-days, computed at a reference temperature, τ, which is estimated by PRISM for a particular set of consumption data. NAC is given by PRISM as:

$$NAC = 365\alpha + \beta H_o(\tau) \qquad (1)$$

where

α = base level (MBtu/day)

β = heating rate (MBtu/°F-day)

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[1] This includes labor and installation for the water heaters, plus a portion of the new gas piping, which also provides gas for space heating.

$H_o(\tau)$ = average annual heating degree days for approximately ten year period, to base temperature[2] τ.

Changes in energy consumption from one period to the next (preferably one-year periods, with complete heating seasons) are calculated as the difference between values of NAC determined for each period.

New methods

Oil tanks not filled. The five Trenton buildings are heated with No. 4 fuel oil. Deliveries are generally made by the truckload, ranging in volume from about 4500 to 6000 gallons. The horizontal, underground tanks are never filled, but the boiler operators usually take dipstick measurements of the oil level in the tank at the time of delivery and also at regular weekly intervals. These depth readings are converted to volume with the use of a chart from the tank manufacturer. The depth, volume, and date, along with deliveries, are recorded on a log which is turned in to the housing authority accounting office every month. These records contain a great deal of data on oil consumption, but extracting the information is a challenge, for several reasons. Data quality varies tremendously from one boiler operator to another. It is not always clear whether dipstick measurements preceded or followed a delivery, except when the boiler operator has recorded both measurements. Sometimes readings are clearly wrong, so data points are lost if they cannot be reconciled. Occasionally volumes listed do not agree with depths. On rare occasions, deliveries are not recorded, although these can usually be found by comparison with invoices, if available. These problems, as well as the large quantity of data, demand a computerized means of systematically processing raw data into a form suitable for further analysis. A spreadsheet-based procedure that we developed has several functions:

- Enables easy data entry and the use of calendar-related functions.
- Checks for consistency between tank depth and volume[3] data and flags periods showing negative consumption, giving the user additional information with which to correct the data point or eliminate it from analysis.
- Enables the user to specify conditions for aggregating consumption to regular intervals of any length. This eliminates some of the noise associated with one- or two-day intervals, and

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[2] The parameter τ is found as that value which maximizes the R^2 statistic (Fels, 1986).

[3] The equation used to calculate the volume of a horizontal cylindrical tank from depth measurements is given in the extended version of this report (Englander and Dutt, 1986).

provides periods of approximately equal length, avoiding disproportionate weighting of short periods[4].

- Results in a file of "clean" data that can then be used as input to PRISM or another model.

Oil to gas equipment conversion. The five Trenton properties changed from heating DHW using the oil-fired space-heating boiler(s) to using two to four gas-fired domestic water heaters. Before the retrofit, the boilers were on all year, and the heating steam header was opened in the fall and closed in the spring. Now, the boilers are shut down in the spring, and turned on again in the fall. Figure 1 shows a plot of oil consumption against mean outside temperature for one of these buildings. Before the retrofit, the boiler was operating on the "elbow" of the line during mild weather. After the retrofit, consumption is strictly a linear function of outdoor temperature with no temperature threshold. PRISM relates consumption to degree days calculated from a specific base temperature, and is not directly applicable. In the post-retrofit case, NAC also depends on the boiler on/off dates, which are to some extent arbitrary. We have developed a calendar-based model which gives NAC as a function of two regression parameters related to building characteristics, normal daily outside temperatures, and boiler on/off dates. Here NAC is expressed as E_{hd} (MBtu/yr), the sum of a normal-year heating component E_h and a normal-year DHW component, E_d:

$$E_{hd} = E_h + E_d \tag{2}$$

where

$$E_h = \sum_{i=m}^{i=n} [a + bT_i] \tag{3}$$

a = parameter determined by regression (MBtu/day)

b = heating slope determined by regression (MBtu/°F-day)

T_i = normal daily average temperature for day i (°F)

m = boiler on date

n = boiler off date

E_d = DHW energy consumption, post-retrofit (MBtu/yr)

The calculated change in consumption between the pre-retrofit period and any given post-retrofit period will thus depend on when the boiler is

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[4] A recent version of PRISM, still in the testing phase, will allow automatic weighting of points according to period length (Hurvich, 1986).

turned on and off. In our analysis, we have calculated E_{hd} for several combinations of boiler season endpoints.

If, following the retrofit, the DHW gas is separately metered, E_d (post-retrofit) is determined as follows. DHW gas use depends on outside temperature, decreasing at higher temperatures. If we assume a linear dependence, with no temperature threshold, E_d is given by:

$$E_d = 365c + d\sum_{i=u}^{i=v} N_i(T_i)T_i \tag{4}$$

where

T_i = ith integer temperature for a distribution of daily average temperatures for a normal year (°F)

N_i = number of days in a normal year with temperature T_i

u = lowest integer temperature

v = highest integer temperature

c,d = intercept at T = 0°F, and slope determined by regression of monthly DHW gas use vs. outside temperature (MBtu/day)

The quantity

$$\sum_{i=u}^{i=v} N_i(T_i)T_i$$

turns out to be the normal-year cooling degree-days at base 0°F. So Equation 4 reduces to

$$E_d = 365[c + dC(0°F)] \tag{5}$$

where

C(0°F) = normal cooling degree-days per day taken at base 0°F (°F-days/day)

DHW fuel not submetered. We encountered a problem with two of the Trenton properties--Kerney Homes and Campbell Homes--where the natural gas supply for the new water heaters was taken off the existing (cooking) gas meters. As a result, post-retrofit gas meter readings include consumption by both uses. In an effort to separate the two, we analyzed pre-retrofit cooking gas consumption patterns in these and other multifamily buildings.

(Englander, 1986). Figure 2 shows monthly-average cooking gas consumption per day plotted against average outside temperature for each metering period. A weather dependence can be seen clearly in these data, with the exception of one outlier which occurs in mild weather. The weather dependence could be due to the temperature dependence of cooking--more cooking at lower temperatures--and use of gas ranges for supplementary space heating. The outlier also has physical significance--this occurred during the period in the fall before the heating header had been opened (and heat was not available to the occupants), yet temperatures were starting to get low. We model cooking gas consumption as a linear function of outdoor temperature, with a correction for the outlier.

Pre-retrofit *annual* cooking gas consumption, E_c (MBtu/yr), is given by:

$$E_c = 365[e + fC(0°F)] + N\delta \tag{6}$$

where

N = number of days in the period associated with the outlier

δ = excess gas use per day due to the outlier (MBtu/day)[5]

and the parameters e and f are analogous to c and d in Equations 4 and 5 and are determined by regression of pre-retrofit monthly gas use with outside temperature[6] . We assume E_c remains unchanged before and after the retrofit. The post-retrofit annual DHW energy consumption is then computed as the difference between the post-retrofit annual gas use for cooking plus DHW (E_{cd}), determined by meter readings, and the pre-retrofit gas use for cooking (E_c):

$$E_d = E_{cd} - E_c \tag{7}$$

E_{cd} is given by:

$$E_{cd} = 365[g + hC(0°F)] \tag{8}$$

where the parameters g and h are analogous to c and d in Equation 5, and are determined by regression of post-retrofit monthly gas use vs. outside

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[5] A first order estimate of this is obtained using the outlier in the pre-retrofit cooking gas consumption data. Although this correction will change from year to year, as it depends on the weather and boiler on/off dates, this estimate is probably adequate, since the outlier amounts to only about 6% of annual cooking gas consumption.

[6] The regression was performed *excluding* the outlier.

temperature. The normalized annual consumption for heat and DHW in the post-retrofit period, E_{hd}, is then computed using Equation 2.

Concurrent heating system retrofits. This is one of the more difficult complications that can arise in estimations of retrofit savings, especially when cooking, DHW, and space heating gas use are not separately sub-metered. The case-in-point is Asbury Park Village, a 12-building public housing complex in Asbury Park, New Jersey. A central boiler originally providing both space heat and DHW was replaced with separate furnaces and water heaters located in each apartment. Gas meters combine the usage for space heating, DHW, and cooking in the post-retrofit period. A detailed study of the retrofits was done (Dutt et al., 1986); only the results are summarized here.

PRISM was used to determine the pre-retrofit base-level gas use, which typically corresponds to average summertime consumption (Fels et al., 1984). Energy used for summertime water heating was estimated by subtracting summer cooking gas use, which in turn was estimated using data from studies of national residential energy use (Meyers, 1981) and submetered data in other New Jersey public housing projects (Englander, 1986). The energy savings due to the DHW retrofit were thus based on summer use only, and probably underestimate the actual savings because of losses, before the retrofit, from underground DHW distribution piping.

Seasonal changes in DHW heating equipment. In several properties operated by the Asbury Park Housing Authority, DHW is heated by the main gas-fired boiler during the winter, while during the summer this boiler is shut off, and a separate, smaller gas-fired boiler is used for water heating.

One building in particular, Lumley Homes, a senior citizen high-rise, has been studied in detail (DeCicco et al., 1986). Here, summer DHW gas use was estimated by summer gas meter readings and coincided with the PRISM base-level estimate.

RESULTS

The heating and DHW consumption, E_{hd}, is well determined for the Trenton buildings in the pre-retrofit period, and ranges from 115 MBtu/apt-year to 167 MBtu/apt-year (Table II)[7]. For this period, the DHW energy consumption, E_d, is not disaggregated from the total.

The post-retrofit DHW energy consumption, E_d, ranges from 30 to 47 MBtu/apt-year. The heating energy consumption, E_h, for this period depends on the dates the boiler is turned on and off. Table II shows values for

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[7] Standard errors shown in Table II are derived in the longer version of this paper (Englander and Dutt, 1986).

this parameter obtained using the period October 15 to May 15, which is typical of the period for which the heating steam header was previously open in these buildings. Table III shows the sensitivity of E_h and savings to the choice of boiler-on period, using typical extremes as limits on the boiler on and off dates.

In the post-retrofit period, E_h, E_d, and E_{hd} are all well determined. Energy savings and percent savings are statistically significant. It is interesting that the choice of boiler-on period does not have a major effect on the results (less than 5% variation in E_{hd}), even though the longest and shortest periods chosen differ by 44 days.

For the period chosen in Table II, savings across buildings vary widely, from -17 (± 4) to 10 (± 3) MBtu/apt-yr, or -15% (± 4%) to 7% (± 4%). As it turns out, the three buildings showing positive savings are buildings where there have been problems meeting peak DHW demand since the retrofit, and therefore less hot water is being provided than before the retrofit. This is an important result, because these systems are scheduled for modification in order to increase capacities. Judging from the two buildings which are meeting the demand (Lincoln and Campbell), we can expect negative savings in all buildings, once the modifications have been made.

Although E_d for the pre-retrofit period is not separately determined, we can compare annualized summer consumption (determined from PRISM base-level estimate), $365\alpha_S$, for this period with the post-retrofit value of E_d (Table II). This parameter ($365\alpha_S$) provides a yardstick against which post-retrofit DHW energy use may be measured. In Lincoln and Kerney, there is essentially no difference between $365\alpha_S$ and E_d. In Donnelly and Wilson, E_d is significantly greater than $365\alpha_S$; in Campbell, E_d is significantly less. A more useful post-retrofit parameter for comparison with $365\alpha_S$ is E_{ds}, defined as follows. Given the outside-temperature dependence of DHW energy use, regression parameters c and d of Equations 4 and 5 can be used to calculate an annualized summer consumption, E_{ds}, as

$$E_{ds} = 365(c + dT_s) \tag{9}$$

where

T_s = an average summertime outside temperature.

A comparison of E_{ds} and $365\alpha_S$ for our buildings yields qualitatively the same results as the comparison between E_d and $365\alpha_S$ (Table II).

In order to extend these savings figures to annual cost savings, it is important to include the effect of price differences between natural gas and No. 4 oil. Table II shows the annual fuel cost savings per apartment, calculated using November 1985 and April 1986 fuel prices[8]. Even at the higher November 1985 fuel oil prices, there is a significant increase in cost in one building with positive savings, and very little change in the other two. Using April's lower prices yields a large cost increase all around. Of course, maintenance costs may be affected by the retrofit as well; we have not evaluated this effect here.

In contrast to the Trenton buildings, retrofits at Asbury Park Village (APV) and Lumley Homes both show positive energy savings. As discussed in the section above, the concurrent heating and DHW retrofits at APV without DHW submetering preclude an estimate of annual savings due to the DHW retrofits alone. Summertime fuel use data, adjusted for typical cooking gas use, suggest a reduction in summertime DHW energy use from 0.13 to 0.09 MBtu/apt-day (Dutt et al., 1986).

The Lumley Homes DHW retrofit involved a separate boiler for summertime water heating and the summertime savings are even more spectacular, going from 0.10 to 0.05 MBtu/apt-day (DeCicco et al., 1986). Here, the DHW retrofit was done in isolation and its effect on energy use was determined using PRISM. The weather normalized annual gas use (for space and water heating and cooking) fell from 134 to 128 MBtu/apt-yr following the DHW retrofit (DeCicco et al, 1986, Table 2). This reduction of 6 MBtu/apt-yr in annual gas use is consistent with 110 days of operation of the summer boiler saving 0.05 MBtu/apt-day. However the PRISM estimate of annual savings has a standard error of 17 MBtu/apt-yr, making the results not statistically significant.

CONCLUSIONS

Problems of measurement of savings from DHW retrofits were resolved in most instances. Energy consumption in oil boilers can be measured where dipstick readings are recorded. Lack of DHW energy submetering requires an analysis of the combined energy use for space and water heating or water heating and cooking. Both required an extension of standard scorekeeping methodology and also led to weather-normalized indices of energy use. The effect of arbitrary start and end dates of boiler operation required an additional model using normal temperatures for each date in the period of operation.

Only in the case of simultaneous heating system retrofits was it impossible to separate out the annual savings from DHW retrofits. In this case, however, change in summertime energy use is an indication of retrofit effectiveness.

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[8] Each of the Trenton buildings receives natural gas service at one of two rates. This is accounted for in the cost savings calculations shown in Table 2.

In the five oil-heated Trenton buildings where the DHW retrofit was a separate water heater, savings in annual energy use for space and water heating varied from -17 (±4) to 10 (±3) MBtu/apt-yr. The three buildings with positive savings also report an inadequate supply of hot water, after the retrofit. We suspect that their savings is primarily the result of reduced hot water availability, and that for comparable hot water output the energy savings would be zero or negative in all these buildings. This is a surprising result that has major implications, since the installation of a water heater separate from the heating system is generally believed to be a significant energy saving opportunity. Surprisingly, even the consumption in mild weather shows no savings in four out of five buildings.

In Asbury Park Village the DHW retrofit could only be evaluated in terms of its effect on summertime consumption. Significant savings were recorded in this case which involved the installation of water heaters in each apartment. Decentralized heating and water heating for apartment buildings with specific reference to Asbury Park Village, are discussed elsewhere (Dutt et al., 1986).

Summertime hot water energy use fell by over 50% at Lumley Homes following the DHW retrofit, a separate boiler that operates only in the summer (unlike those in the Trenton buildings, which operate all year long). The Lumley Homes result, in contrast to the Trenton retrofits, shows large (50%) savings in summertime gas use following the installation of a separate steam boiler for summertime water heating. The DHW gas use was not submetered, however, and the annual savings in gas use for space and water heating, though the correct magnitude, was not statistically significant.

Additional measurements, such as those carried out at Lumley (DeCicco and Dutt, 1986), will need to be made in the Trenton buildings in order to understand the boiler and other heat losses. These studies should lead to the identification of energy consumption opportunities for these buildings as well as guidelines for improved specification of water heating retrofits in other buildings.

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Table I. Summary of building characteristics.

PROPERTY	Lincoln Homes	Donnelly Homes	Kerney Homes	Campbell Homes	Wilson Homes	Asbury Park Vill.	Lumley Homes
BUILDING ID	5-1	5-2	5-4	5-5	5-6	7-1	7-6
CITY OR TOWN	Trenton	Trenton	Trenton	Trenton	Trenton	Asbury Park	Asbury Park
OWNERSHIP	public	public	public	public	public	public	public
BLDG. CONFIGURATION	2s, 3s	2s dup/3s wk-up	3s	3s	3s	2s	6s elev
GR. FLOOR AREA (ft^2)	86,744	252,033	72,629	59,184	167,878	89,176	39,200
CONSTRUCTION DATE	1939	1939	1953	1980	1954	1941	1963
# UNITS	118	376	102	81	219	126	60
# BLDGS.	8	21	5	5	9	12	2
FAM/SEN/MIX	family	family	family	family	family	family	senior
HEATING PLANT:							
TYPE	(2)Clvr Brks,stm	(3)Clvr Brks,stm	(2)H.B. Smith,stm	(2)H.B. Smith,stm	(2)H.B. Smith,stm	(2)Superior,stm	(2)Gibralter,stm
FUEL	#4 Oil	#4 OIL	#4 Oil	#4 Oil	#4 Oil	Nat. gas	Nat. gas
INST. DATE	1973	1973	1980	1980	1982	c. 1970 **	1963
DISTRIB. SYS.	2-p steam	2-p steam	2-p steam	2-p steam	2-p steam	2-p steam	2-pipe steam
DHW SYS. CONFIG.	steam converters	steam converters	steam converters	steam converters	boiler jacket wtr	main blr/coil/tnk	main blr/coil/tnk
FUEL (IF SEPARATE)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
DHW RETROFIT CONFIG.	(3) wtr htrs/tank	(4) wtr htrs/tank	(2) wtr htrs/tank	(2) wtr htrs/tank	(3) wtr htrs/tank	apt. water heaters	dnkey blr/coil/tnk
FUEL (IF SEPARATE)	Nat. gas	Nat. gas	Nat. gas	Nat. gas	Nat. gas	Nat. gas	Nat. gas

** During the summer/fall of 1983, gas-fired, warm-air furnaces were also installed in each apartment, at the same time as the DHW retrofit.

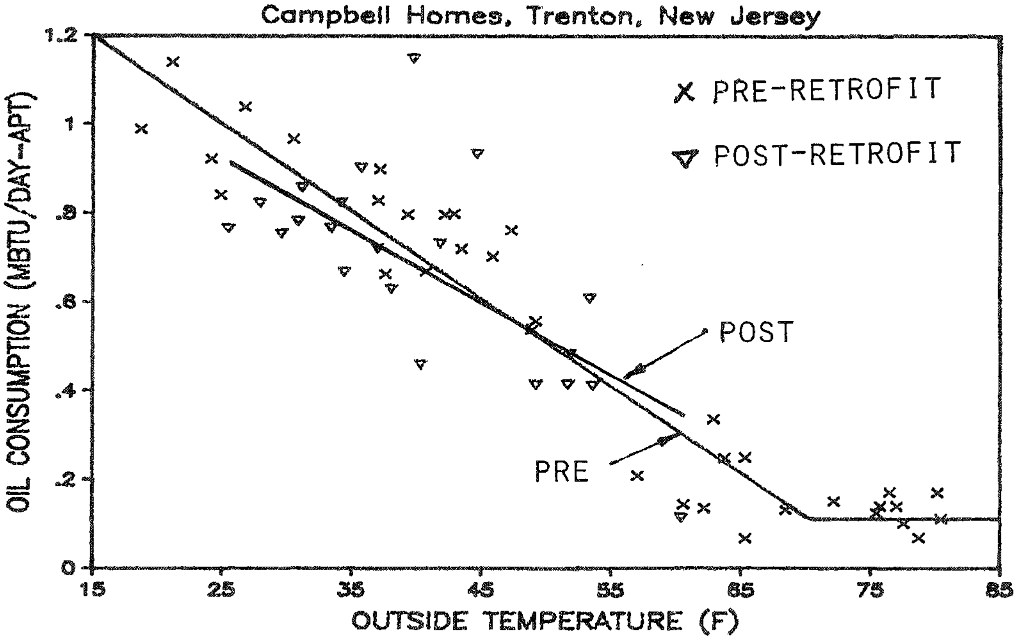

Figure 1. Pre- and post-retrofit oil consumption versus mean outside temperature.

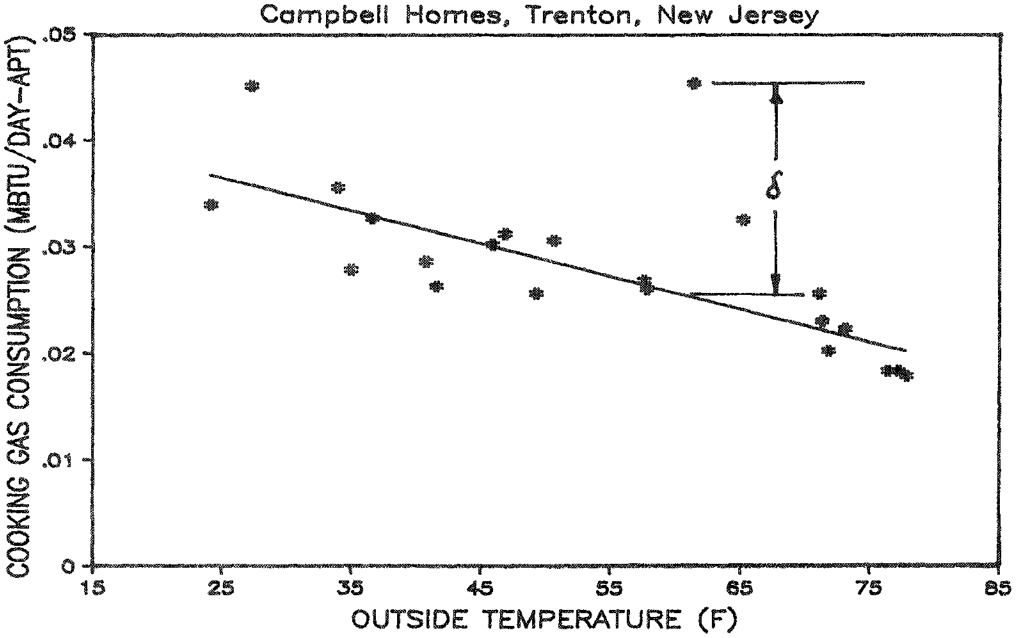

Figure 2. Pre-retrofit cooking gas use versus mean outside temperature; outlier represents use of gas ranges for space heating.

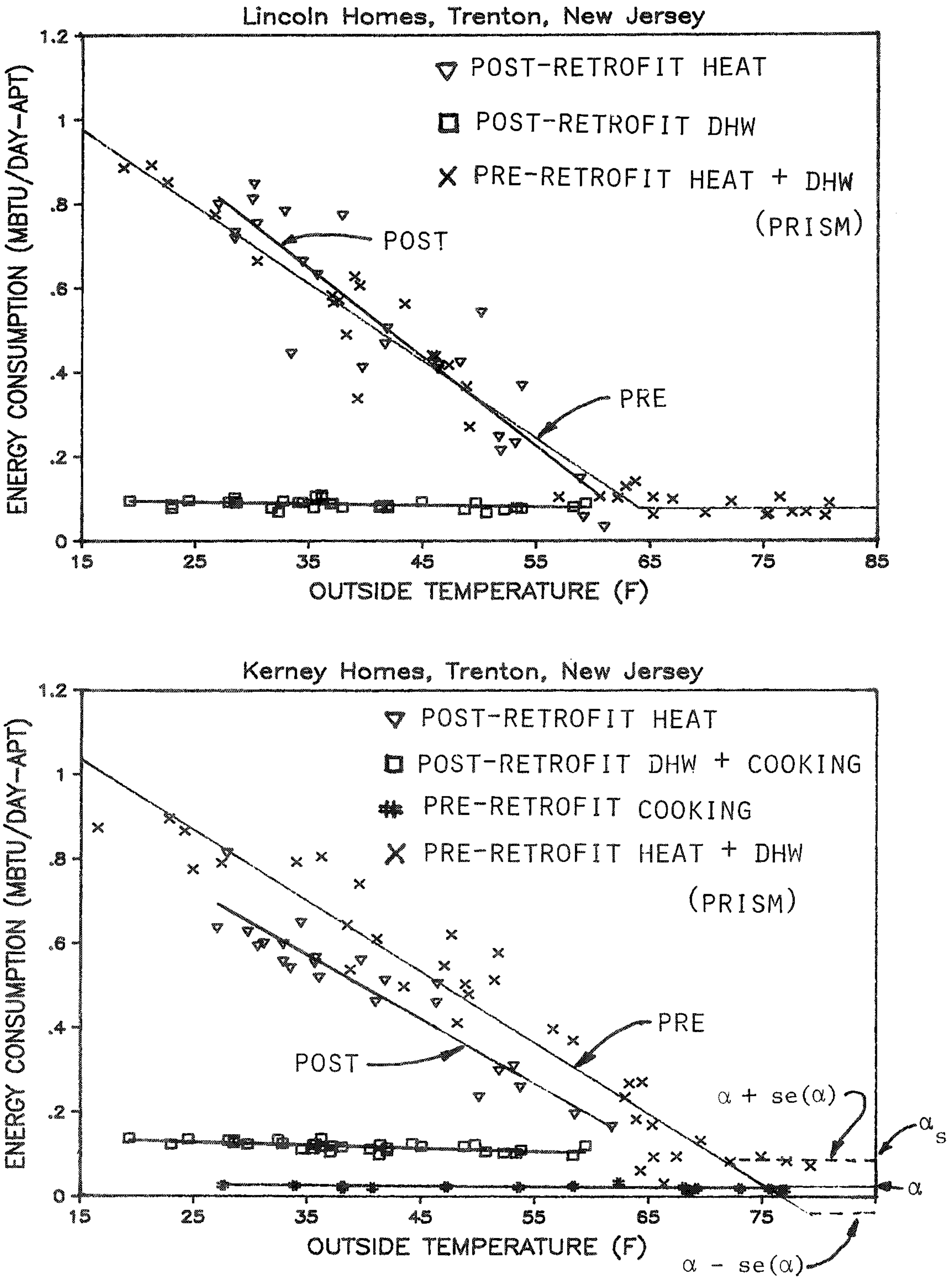

Figure 3. Energy use by component versus mean outside temperature for two public housing projects before and after a DHW retrofit.