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MEASURED SPACE-COOLING ELECTRICITY SAVINGS FROM STANDARD-ENERGY CONSERVATION MEASURES, RADIANT BARRIERS, AND HIGH-EFFICIENCY WINDOW AIR CONDITIONERS

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ABSTRACT

A cooperative field test was performed in Tulsa, Oklahoma, to determine the space-cooling electricity consumption of low-income homes equipped with window air conditioners, the reduction in consumption due to energy conservation measures (ECMs) installed under Oklahoma's Weatherization Assistance Program (WAP), and the additional reduction due to two ECMs designed to reduce space-cooling electricity consumption: attic radiant barriers and replacement of low-efficiency window air conditioners with high efficiency units.

Eighty-one single-family, owner-occupied houses were divided into a control group and three treatment groups: ECMs performed under Oklahoma's WAP, WAP ECMs plus a truss-mounted attic radiant barrier, and WAP ECMs plus a high-efficiency window air-conditioner to replace a less efficient unit. Pre-weatherization data were collected during the summer of 1988 and post-weatherization data were collected the following summer. Air-conditioning electricity consumptions and indoor temperatures were monitored weekly. Air-conditioning energy use models and regression analyses were employed to normalize annual space-cooling electricity consumptions and savings to average outdoor temperatures and pre-weatherization indoor temperatures.

Normalized pre-weatherization air-conditioning electricity consumption averaged 1664 kWh/year ($119/year). Significant reductions in air-conditioning electricity consumption were not produced by WAP ECMs or by combining a truss-mounted attic radiant barrier with them. Replacing low-efficiency air conditioners with high-efficiency units in all houses was not cost-effective. An average normalized reduction in air-conditioning electricity consumption of 535 kWh/year ($38/year) resulted from replacing one low-efficiency air conditioner per house with a high-efficiency unit at a cost of $947/house. These savings and cost-effectiveness are improved by targeting houses for replacement based on higher than average consumption: average normalized savings of 1069 kWh/year ($76/year) were obtained at a cost of $999/house in houses with air-conditioning electricity consumption greater than 2500 kWh/year.

INTRODUCTION

An appreciable amount of the energy costs for families in southern climates occurs during the cooling season. However, research directed at improving the efficiency of buildings in such climates has not received the same focus as in cold climates. A cooperative field test was performed in Tulsa, Oklahoma, to determine the space-cooling electricity consumption of low-income houses equipped with window air conditioners, the reduction in space-cooling electricity consumption attributed to the installation of energy conservation measures (ECMs) as typically installed by Oklahoma's Low-Income Weatherization Assistance Program (WAP), and the additional reduction achieved by the installation of two ECMs designed to reduce space-cooling electricity

consumption: replacement of low-efficiency window air conditioners with high-efficiency units and the installation of attic radiant barriers.

FIELD TEST DESIGN

An experimental plan documents details of the field test design (Ternes and Hu 1989). Eighty-one houses in Tulsa, Oklahoma, were monitored: 20 were assigned to a non-treatment group in which no ECMs were installed (control houses), 23 received ECMs performed under Oklahoma's WAP (weatherization only houses), 19 received ECMs as currently performed under Oklahoma's WAP plus a truss-mounted attic radiant barrier (radiant-barrier houses), and 19 received ECMs as currently performed under Oklahoma's WAP plus a high-efficiency window air conditioner in replacement of a less efficient unit (air-conditioner replacement houses). Pre-weatherization data were collected for all houses during one cooling season (June to September 1988) and post-weatherization data were collected during the following cooling season (May to September 1989). Important characteristics of houses included in the field test were that occupants were low-income, occupants were owners of their houses, houses were single-family detached houses but not mobile homes, and houses were cooled by one or two electric window air conditioners.

The following data, basically adhering to a residential monitoring protocol (Ternes 1987), were manually collected weekly for all houses during the two summer test periods: house gas consumption, house electricity consumption, and air-conditioning electricity consumption (each air conditioner in a house was metered separately). Hourly indoor temperatures were monitored in each house and hourly outdoor weather data were monitored at three nearby sites. The indoor temperature was monitored in the room with the window air conditioner; if two air conditioners were in a house, temperature was monitored in the room with the air conditioner operated the most (as reported by the occupants).

HOUSE AND OCCUPANT CHARACTERISTICS

The houses ranged between 4 and 75 years old, the average being 41 years. Almost all houses had a crawlspace and were single-story. The floor area of the houses averaged 1244 ft^2, with 78% being between 900 and 1500 ft^2. Twenty-seven percent of the houses had two window air conditioning units, with the remaining having just one unit. The average age of the units was 8 years, with 72% between 4 and 12 years old. Nameplate cooling capacities ranged from 4000 to 28,000 Btu/h, with approximately half being 18,000 Btu/h. Few houses had any floor insulation, 54% had no wall insulation, and 9% had no attic insulation. Attic insulation thickness was usually between 1 and 3 in. Window area in the houses averaged 145 ft^2, ranging from 48 to 443 ft^2. Most of this window area was single pane without storm windows.

ENERGY CONSERVATION MEASURES

Description of Measures

A standard set of ECMs (selected specifically to reduce space-heating energy consumption) is installed in each low-income home serviced by the Oklahoma WAP. Caulking and weatherstripping is performed first. Attic insulation levels are increased to a thermal resistance of R-19 using blown cellulose insulation, attics are properly vented, and minor roof leaks are repaired.

Storm window repair or installation is the final ECM. Other minor repairs to the house may also be performed under the program.

An attic radiant barrier consists of material with one or two low-emissivity surfaces to reduce far-infrared-radiation heat transfer occurring between the roof and the top of the attic insulation. The barrier was attached to the underside of the roof rafters and on the gabled ends of the attic.

In each air-conditioner replacement house, one window air conditioner with an Energy Efficiency Ratio (EER) less than or equal to 7.0 was replaced by a high-efficiency unit (EER greater than or equal to 9.0) having about the same capacity as the original unit. In houses with two existing units meeting this criterion, the unit with the greater pre-weatherization electricity consumption was replaced. All units older than four years were assumed to be eligible for replacement because actual EER ratings were not available. A minimum EER of 9.0 was selected for the replacement units to ensure that they met minimum efficiency standards for room air conditioners as stipulated by Congress (National Appliance Energy Conservation Act of 1987).

Installed Measures and Costs

Costs for installing all ECMs are summarized in Table 1. Although the control group was not weatherized until after the field test was completed, costs for the control group are included to help demonstrate their equivalency with the other three groups.

The average costs for the weatherization work performed under Oklahoma's WAP were nearly the same in each group, averaging between $836 and $885 per house. Installation of the attic radiant barriers in the truss-mounted configuration averaged $394 per house and ranged between $385 and $445. Because the radiant barrier material was donated, these costs include an estimated cost of $250 per house for material. The installation costs (materials plus labor) for the air conditioners ranged from $546 to $1488, and averaged $947.

AIR-CONDITIONING ELECTRICITY ANALYSES

Air-conditioning electricity savings was defined to be the annual savings normalized to an average weather year for Tulsa, Oklahoma, and the average pre-weatherization indoor temperature for each house. Normalizing the annual savings for both indoor and outdoor temperature provides the best estimate of the actual savings in each house due to the ECMs installed.

Normalized annual air-conditioning electricity consumptions used to calculate savings were estimated from the pre- and post-weatherization data using air-conditioning electricity consumption models and regression analyses to account for the following factors: time periods over which data were collected were unequal and did not cover entire summer periods, pre- and post-weatherization outdoor temperature conditions were different and not equal to the typical outdoor temperatures desired for normalization, and post-weatherization indoor temperatures were not equal to pre-weatherization temperatures.

An idealized relation between weekly air-conditioning electricity consumption and a weekly "driving force" temperature (either average weekly outdoor temperature or outdoor-indoor temperature difference) has three regions (see

Figure 1): no air conditioning is required at sufficiently low temperatures, electricity consumption is non-zero but not a function of temperature in a transition region, and a linear relationship region at higher temperatures.

The electricity usage behavior exhibited in the transition region is due, in part, to use of a weekly average temperature to characterize the driving force. Except in the warmest climates, cool periods several days in duration are likely to occur during the summer when air-conditioning is not required. The relationship between air-conditioning electricity consumption and the temperature driving force is different for weeks that include these cool periods than for those that do not. This occurs because the effect of these cool periods on electricity consumption is limited (electricity consumption cannot drop below zero) but is not limited on the driving force temperature. For example, assume that 350 kWh is used to cool a house on a day with an average outdoor temperature of 85°F and that the daily outdoor temperature for the next six days is sufficiently low so that no air conditioning is needed. The average air-conditioning electricity consumption for this period is 350 kWh/week. If the average outdoor temperature of these remaining six days was 80°F, the average weekly temperature would be 81°F, whereas the average weekly temperature would be 76°F if the daily temperature for the six days was 75°F. Thus, weekly electricity consumption becomes unrelated to the weekly outdoor temperature under this type of condition. Because the house indoor temperature is able to float below the setpoint of the air conditioner (the thermostat only controls above its setpoint), the same behavior occurs even if outdoor-indoor temperature difference is considered.

Data for each house were examined individually to identify the data appropriate for the three electricity consumption-temperature regions defined above from Figure 1. Data falling within the transition region were used to estimate a transition consumption constant for each house. This constant was zero in many houses (there was not a discernible transition region). Data falling within the linear region were used with the house models described below to develop regression equations.

Two air-conditioning electricity consumption models were used. The models assumed that the electricity consumption of each air conditioner was linearly related to either the temperature difference between the inside and outside of the house or to just the outdoor temperature. Two models were needed because the indoor temperature was monitored in just one room of the house and, in houses with two air conditioning units, this temperature corresponded to only one of the units. In houses with two air conditioners, the indoor temperature was monitored in the room with the air conditioner that the occupants reported was operated the most (labeled AC1 for the field test). Consequently, the electricity consumption of this air conditioner (presumably a larger electricity consumption than the second unit) was normalized to both indoor and outdoor temperature. The second air conditioner (AC2) was only normalized to outdoor temperature. The models used were

$$E_{AC1} = A + (B * DT) \quad \text{and}$$

$$E_{AC2} = A + (B * To)$$

where

E_{AC} - electricity consumption of the air conditioner,
DT - outdoor minus indoor temperature difference,
To - outdoor temperature,
A - intercept coefficient (determined by regression), and
B - slope coefficient (determined by regression).

Linear regression techniques were used to estimate the parameters, A and B, for the pre- and post-weatherization periods for each air conditioner. Although the electricity consumption data were collected primarily on a weekly basis, the collection periods did vary in duration. Consequently, the electricity consumptions used in the regression analyses were normalized to weekly consumptions by dividing the electricity consumption for the period by the duration of the period in weeks. The temperatures used in the analyses were the average temperature for the period, and the average temperature difference between hourly indoor and outdoor temperatures for the period.

Weeks with little or no air-conditioning electricity consumption in the linear region were not ignored in the analyses. Weeks with low consumption indicate times when occupants choose not to operate the air conditioner even though a large temperature difference existed and they tended to operate the unit at this temperature difference at other times. Including these data in the regression retains occupant behavior within the analysis, although coefficients of determination (R^2) decrease and uncertainty increases.

Pre- and post-weatherization normalized annual electricity consumptions for each air conditioner were calculated using the estimated pre- and post-weatherization regression values for A and B found for each air conditioner, the transition electricity consumption constants identified for each air conditioner, average outdoor temperatures from a Typical Meteorological Year (TMY) weather tape for Tulsa, Oklahoma, and the average pre-weatherization indoor temperature for each house (applicable for the AC1 units only). Weekly average outdoor temperatures and temperature differences were calculated using the pre-weatherization indoor temperature and TMY outdoor temperature data for dates between April 23 and October 14. This 25-week summer period was chosen because the average outdoor temperature was generally greater than 70°F and, thus, space-cooling was likely required. This choice excludes the electricity consumption-temperature region when no air conditioning is required. Each average weekly outdoor temperature or temperature difference was then used with values for A and B for each air conditioner to estimate a weekly air-conditioning electricity consumption. If the electricity consumption determined using the regression coefficients was less than the transition consumption constant, the weekly value was set equal to this value. The weekly values were summed to obtain an estimate of the normalized annual electricity consumption of each air conditioner.

AIR-CONDITIONING ELECTRICITY CONSUMPTION AND SAVINGS RESULTS

Air-conditioning electricity consumptions and savings for 78 of the 81 field test houses will be discussed. Two houses (one from the control group and one from the weatherization only group) were dropped from the analysis because their air-conditioning electricity savings were not within four standard deviations of the average of their respective group. A third house, part of the air-conditioner replacement group, was dropped because the existing air conditioner did not qualify for replacement.

Over half the coefficients of determination for the AC1 analysis (using outdoor-indoor temperature difference) were greater than 0.8 and most were greater than 0.6: the R^2 was greater than 0.6 in 74% of the houses for the pre-weatherization period and in 85% for the post-weatherization period. Coefficients for the AC2 analysis (using only outdoor temperature) were not as high: the R^2 was greater than 0.5 in only 56% of the houses for the pre-weatherization period and in 44% for the post-weatherization period.

Air-Conditioning Electricity Consumption

Total (AC1 and AC2) pre-weatherization air-conditioning electricity consumptions of the field test houses averaged 1664 kWh/year, ranging between 8 and 4701 kWh/year. Figure 2 shows that one-third of the houses used less than 1000 kWh/year (about 10% used less than 250 kWh/year) and few houses (about 10%) used 3000 kWh/year or more. Figure 3 shows that the average pre-weatherization air-conditioning electricity consumptions of the four groups differed by only several hundred kWh/year: 1478 kWh/year for the control houses, 1803 kWh/year for the weatherization only houses, 1452 kWh/year for the radiant-barrier houses, and 1913 kWh/year for the air-conditioner replacement houses. An analysis of variance indicated that these average pre-weatherization consumptions were equal at confidence levels down to 75%.

In houses with two air conditioners, the average electricity consumption of the AC1 air conditioners was 1564 kWh/year and the AC2 air conditioners was 496 kWh/year (the AC2 value excludes several houses with a second air conditioner that never ran). With only one exception, the AC1 consumption was always greater than the AC2 consumption. These results imply that the air conditioner with the greatest electricity consumption in each house was properly identified by the occupants at the start of the study and that indoor temperature was monitored with the more important unit from an energy consumption perspective.

Air-Conditioning Electricity Savings

Normalized air-conditioning electricity savings averaged 107 kWh/year for the control group, -31 kWh/year for the weatherization only group, -52 kWh/year for the radiant-barrier group, and 535 kWh/year for the air-conditioner replacement group (see Figure 3). Both pre- and post-weatherization AC1 consumptions were normalized to the pre-weatherization indoor temperature measured in each house, which averaged 81°F.

An analysis of variance indicated that, at the 95% confidence level, there were significant differences between the average air-conditioning electricity savings of the four groups. Using Duncan's multiple range test at the same confidence level, the savings of the air-conditioner replacement group was determined to be significantly different from the other three groups and the savings of the remaining three groups were not significantly different from each other. These analyses were performed without considering the variance in the individual house savings estimates (i.e., the analyses were performed assuming the individual house savings were known without error).

The distribution of individual house air-conditioning electricity savings for each group is shown in Figure 4. Each group included houses with positive and negative savings. There were eight houses with savings greater than 500 kWh/year in the air-conditioner replacement group, whereas only two or three such houses were in each of the other three groups. The only two houses with savings greater than 1500 kWh/year were both in the air-conditioner replacement group. Although a large percentage (about 75%) of the houses in the weatherized only group experienced positive savings (about the same percentage as found in the air-conditioner replacement group), the magnitude of the negative savings experienced in the remaining weatherization only houses was quite large (larger than the other three groups).

The air-conditioning electricity savings of the houses in the air-conditioner replacement group were positively correlated to pre-weatherization air-conditioning electricity consumption. Three houses with pre-weatherization consumption of approximately 2500 kWh/year had negative savings. Reasons for these houses not following the trend for the other houses are not known. No correlation was found between savings and pre-weatherization consumption for the other three groups.

DISCUSSION

Coefficients of determination (R^2) for space-heating analyses are generally greater than those obtained for this cooling analysis. Coefficients greater than 0.8 were obtained in more than 90% of houses studied in a previous experiment using submetered space-heating energy consumption and indoor temperature (Ternes et al. 1990). Several reasons for this difference are proposed:

1. Air-conditioning consumption is influenced by at least three weather variables (temperature, humidity, and solar insolation), whereas space-heating energy consumption is strongly dependent on temperature alone. Prior experience and exploratory investigations indicated that multiple regression analysis of weekly air-conditioning consumption data does not considerably improve correlations. Regression coefficients often lack physical meaning, making extrapolations uncertain.
2. Swing periods, when average outdoor and indoor temperatures are near equality, can distort regressions. These periods usually occur at the start and end of the winter (especially in colder climates) and are often ignored in space-heating analysis (Meier et al. 1986). Summers can be constant swing periods because outdoor temperatures often oscillate above and below house indoor temperature over a day and cool periods occurring in the summer allow air conditioners to be turned off for short periods.
3. Control of window air conditioners is likely more occupant dependent and sporadic than central heating systems.

Therefore, the relatively high coefficients of determination obtained from the AC1 analysis (regressions were based on outdoor-indoor temperature differences) were surprising. Coefficients for the AC2 analysis were not as good because the regression was based on outdoor temperature only. Additionally, these second air conditioners were used much less frequently and, thus, more randomly than the main AC1 air conditioners. The high coefficients for the AC1 analysis support the importance of measuring indoor temperature and lend credibility to the field study results.

The average air-conditioning electricity consumption of the field test houses was 1664 kWh/year. The current cost for electricity in the Tulsa area during the summer months (June to September) is $0.06447/kWh for the first 1000 kWh and $0.07147/kWh for any consumption above 1000 kWh. Using the higher rate, the average air-conditioning cost was $119/year. Assuming this consumption can be reduced 50% by an optimum set of ECMs (even though the best group savings in the field test was less than 30%), a maximum savings of about 800 kWh/year ($57/year) would be expected for these houses. Although only 10% of the houses used more than 3000 kWh/year, a maximum savings of 1500 kWh/year ($107/year) would be expected if these houses were targeted.

ECMs installed under Oklahoma's WAP and combined with a truss-mounted attic radiant barrier did not produce space-cooling energy savings that could be measured in the field test. Some savings were expected from these ECMs even though the ECMs installed under the WAP are justified for space-heating rather than space-cooling reductions. Reasons for the lack of savings are not known. Two possible explanations are that ECMs that keep heat out of the house also tend to keep heat in the house (which may be an important consideration when dealing with window air conditioners that are controlled manually as much as by a thermostat) and the lack of wall insulation may have reduced any benefits. The equivalency of the groups is not a likely factor because a random assignment process was followed, pre-weatherization consumptions were statistically the same, and costs for ECMs installed under the WAP were the same (implying the houses required the same degree of improvement).

The gross savings of 535 kWh/year ($38/year) measured in the air-conditioner replacement group was statistically different from the control group and the other two groups receiving ECMs from the WAP. Therefore, these savings can be attributed to just the replacement of high-efficiency air conditioners. There is some question as to whether these savings should be adjusted by the control group or the weatherization only group; consequently, no adjustments are presented in this paper.

At an average installation cost of $947, the replacements are not likely cost effective (simple payback period of just under 25 years). Targeting units for replacement based on above average consumption would improve savings and cost-effectiveness. For houses with pre-weatherization air-conditioning electricity consumption greater than 2500 kWh/year, the average savings of the replacements was 1068 kWh/year ($76/year) and the average installation cost was $999. The simple payback period for this approach is about 13 years.

CONCLUSIONS

The following are concluded for low-income houses located in Tulsa, Oklahoma which have one or two window air conditioners and are maintained at 81°F during the pre-weatherization summer period:

1. Programs directed at reducing space-cooling electricity consumption likely need to be targeted at high-electricity consumers and/or be inexpensive to achieve cost-effectiveness. Program savings are limited by current air-conditioning electricity consumption which averaged 1664 kWh/year ($119/year).
2. Significant reductions in air-conditioning electricity consumption were not produced by ECMs installed under Oklahoma's WAP or by combining a truss-mounted attic radiant barrier with these ECMs. In houses with similar thermal characteristics as those tested (no wall insulation and 1-3 in. of attic insulation) and given that attic insulation is added for

space-heating energy reductions, additional expenditures for measures outside the attic are likely to be more effective at reducing air-conditioning electricity consumption (such as for air-conditioner replacements or perhaps wall insulation).

3. Replacing low-efficiency air conditioners with high-efficiency units in all houses is likely not cost-effective. An average reduction in air-conditioning electricity consumption of 535 kWh/year ($38/year) was obtained from replacement of one low-efficiency air conditioner per house (EER less than 7.0) with a high-efficiency unit (EER greater than 9.0) at a cost of $947/house.
4. Targeting users with high air-conditioning electricity consumption to receive replacement air conditioners increases savings and cost-effectiveness because savings depend on pre-replacement consumption, although bottom-line economics depend on actual installation and electricity costs. Average savings of 1069 kWh/year ($76/year) were obtained at a cost of $999/house in houses with air-conditioning electricity consumption greater than 2500 kWh/year. The social implications of preferentially selecting occupants with high electricity consumption over energy-conscious occupants needs to be considered in following such an approach.

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Table 1. Average energy conservation measure costs per house

Energy conservation measure	Average group cost ($)			
	Control	Weatherization only	Radiant barrier	Air-conditioner replacement
Weatherization:				
Caulking and weatherstripping	331	325	367	316
Storm window	430	351	350	421
Attic insulation	98	109	120	124
Repair	26	52	39	23
Total	885	836	876	884
Radiant barrier	0	0	394*	0
Air conditioner	0	0	0	947
Total	885	836	1270	1831

*Assumes $250/house for material. Cost is estimated because the radiant barrier material was donated.

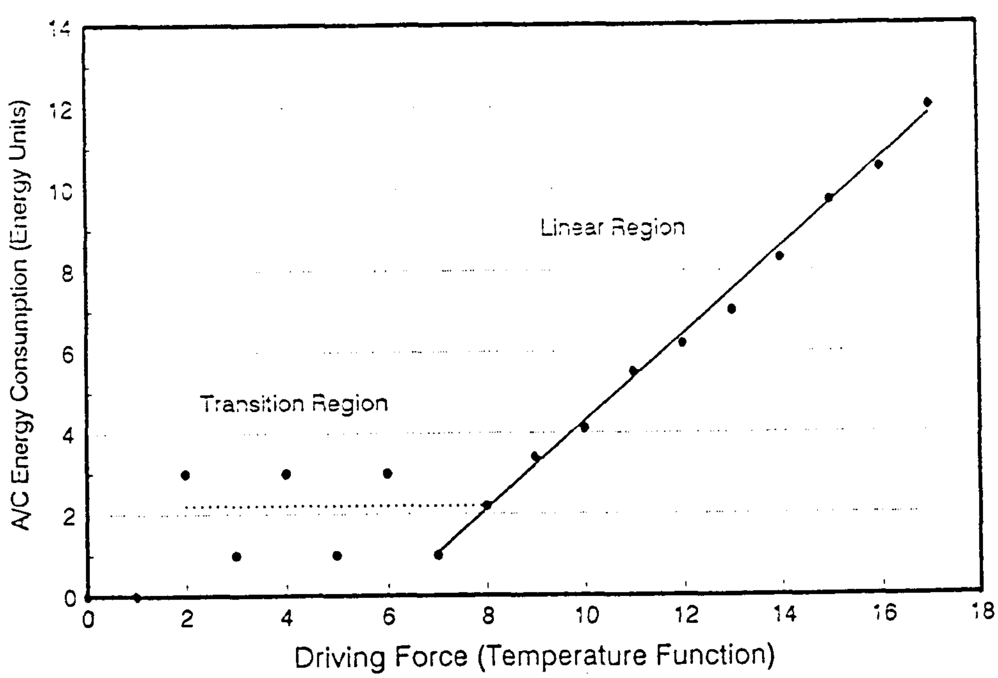

Figure 1. Air-conditioning electricity consumption as a function of a weekly "driving force" temperature (either average weekly outdoor temperature or outdoor-indoor temperature difference) for an idealized situation.

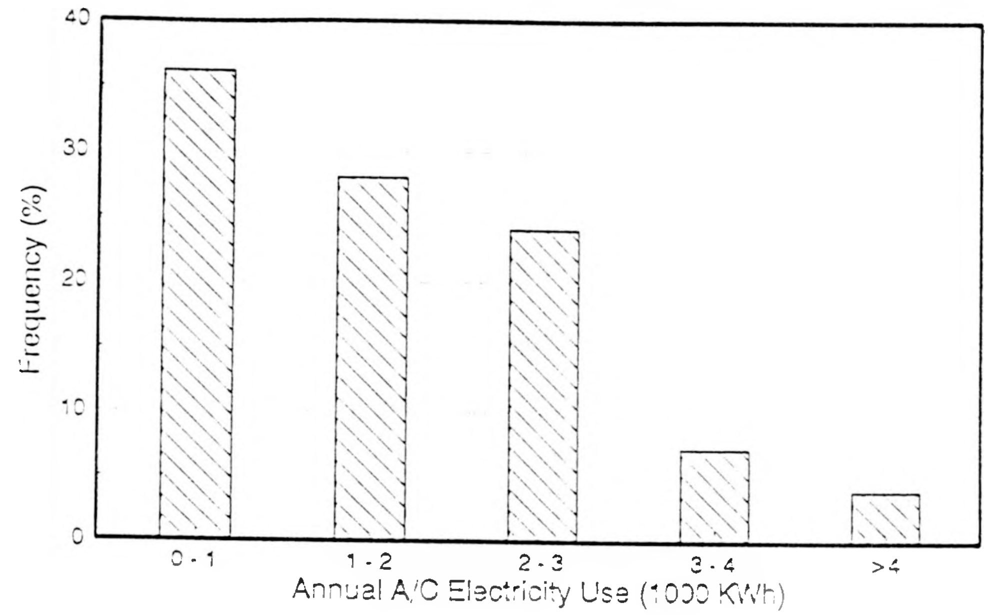

Figure 2. Histogram of normalized pre-weatherization air-conditioning electricity consumption.

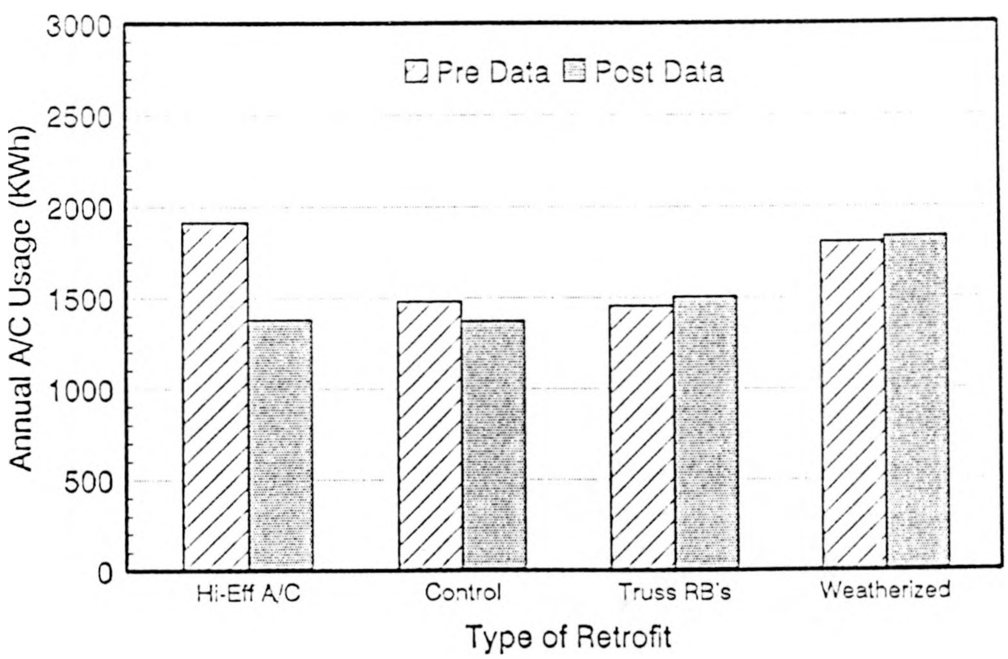

Figure 3. Average normalized pre- and post-weatherization air-conditioning electricity consumption for the four groups of field test houses.

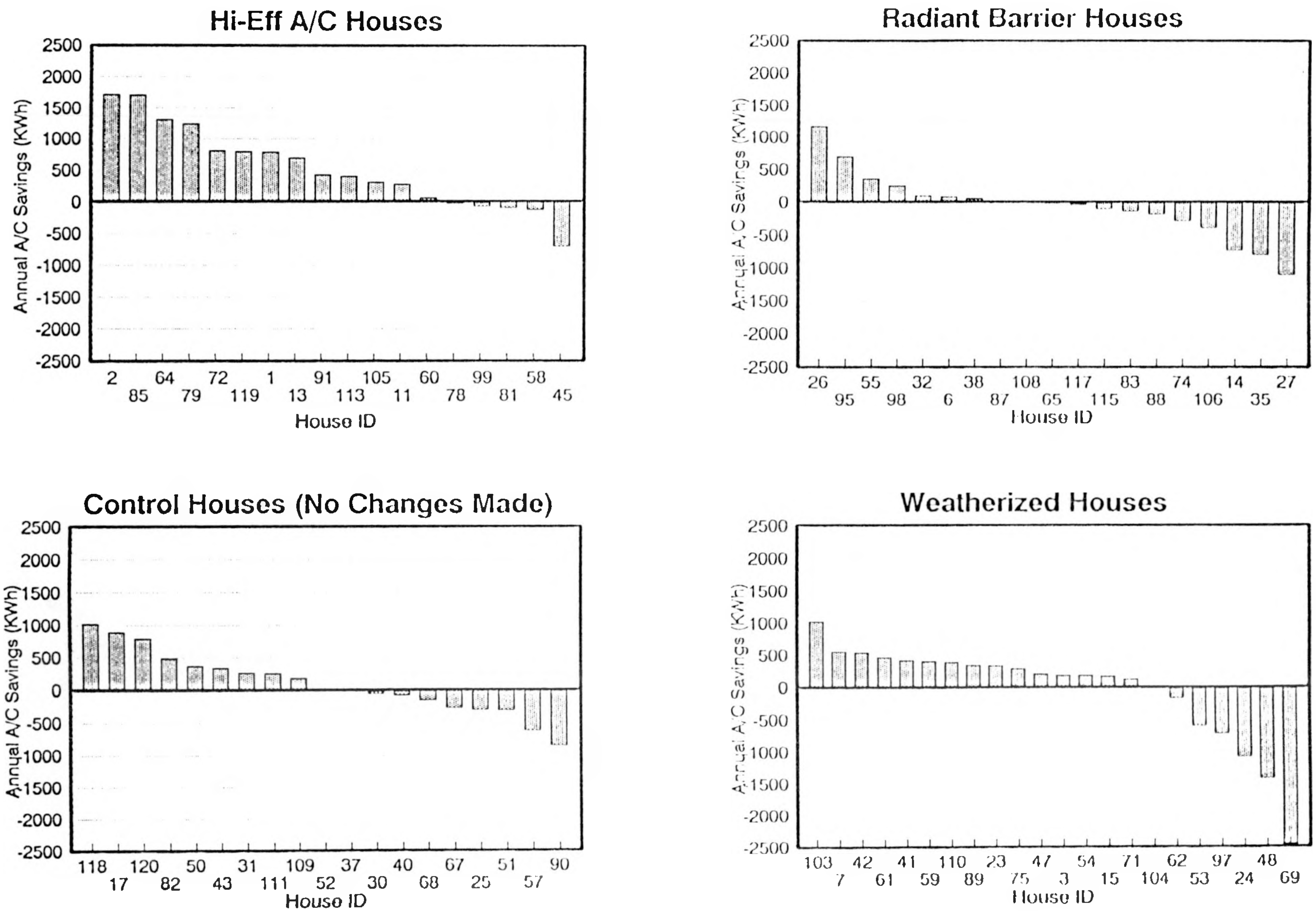

Figure 4. Distribution of individual normalized house air-conditioning electricity savings for the four groups of field test houses.