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TEXAS FIELD EXPERIMENT: Performance of the Weatherization Assistance Program in Hot-Climate, Low-Income Homes

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ACRONYMS

BWR	Building Weatherization Report
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
GETCAP	Greater East Texas Community Action Program
MHEA	Manufactured Home Energy Audit
NAC	normalized annual consumption
NACC	normalized annual cooling consumption
NAHC	normalized annual heating consumption
NEAT	National Energy Audit Tool
NIALMS	Nonintrusive Appliance Load Management System
NOAA	National Oceanographic and Atmospheric Administration
ORNL	Oak Ridge National Laboratory
PHS	Programs for Human Services
PRISM	Princeton Scorekeeping Method
RECS	Residential Energy Conservation Survey
SIR	savings-to-investment ratio
SPEED	single-point electric end-use disaggregation
TDHCA	Texas Department of Housing and Community Affairs
TMY	Typical Meteorological Year

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- **The Texas Department of Housing and Community Affairs (TDHCA)—**TDHCA is the state grantee office, located in Austin, Texas, that implements the Weatherization Assistance Program in Texas for the U.S. Department of Energy. TDHCA arranged for the cooperation of the local weatherization agencies that deliver the Program in Beaumont and Nacogdoches. TDHCA also arranged for the gas utilities to provide billing data for the study.

- **Programs for Human Services (PHS)—**PHS is the local weatherization agency in Beaumont, Texas, that delivers weatherization services for TDHCA. PHS selected homes for the study, performed an EASY audit on each home, and installed weatherization measures.

- **Greater East Texas Community Action Program (GETCAP)—**GETCAP is the local weatherization agency in Nacogdoches, Texas, that delivers weatherization services for TDHCA. GETCAP selected homes for the study, performed an EASY audit on each home, and installed weatherization measures.

- **Entergy—**Entergy is the electric utility that serves the PHS and GETCAP areas. Entergy assisted in installing the electric submetering equipment and provided funds to install new air conditioners in the study homes.

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EXECUTIVE SUMMARY

A number of evaluations of the U.S. Department of Energy (DOE) Weatherization Assistance Program (the Program) both at the national and state level have reported space-heating energy savings attributable to the Program that are lower in hot-climate households than in cold-climate households. In addition, previous program evaluations in hot climates based on analyzing monthly utility bills have been able to measure the space-heating savings occurring in hot-climate dwellings, but they have been unable to detect any significant electric cooling savings. Therefore, DOE sponsored a study by Oak Ridge National Laboratory (ORNL) to investigate the response of low-income homes in hot climates to weatherization and certain methods to improve weatherization performance.

The Texas Field Experiment was initiated in late 2000 and was performed using homes selected from two weatherization agencies in southeastern Texas. Local agencies recruited 57 homes (both site-built single-family homes and mobile homes) for the field study, although only 35 of the original 57 houses remained at the end of the study. About 60% of these homes were electrically heated and the rest were heated with natural gas. A pre- and post-weatherization experimental design was used. The pre-weatherization period for each house began between February and July 2001. The homes were weatherized between May and November 2002, and post-weatherization data were collected through October 2003.

Two groups of homes were used in the field study: (a) 17 homes that were weatherized following the recommendations of the Texas EASY audit and Texas' standard auditing procedures (the standard procedures group) and (b) 18 homes (the demonstration group) that were weatherized based primarily on the recommendations of the DOE-supported Weatherization Assistant (Version 7) which includes the National Energy Audit Tool (NEAT) and the Manufactured Home Energy Audit (MHEA). Although an original intent of the field study had been to compare the energy savings achieved under these two approaches, this analysis was not performed because, in the end, similar measures were installed under both approaches and attrition reduced the number of homes in each group to the point that statistically valid comparisons could not be made. Therefore, analyses of energy consumptions and savings, indoor temperatures, and load profiles were performed for the two groups as a whole rather than separately.

A whole-house electric monitoring system was installed in each house that allowed appliance-specific load data to be collected without installing meters on specific appliances. The system also provided the capability to monitor indoor temperature at one location in each home. For the field study, the temperature monitor was typically installed in a living or family room where the occupants spent most of their waking hours. One limitation of the indoor temperature data is that a single indoor temperature monitored in a house may not accurately reflect the temperatures of other parts of the house, especially in the houses that were not centrally heated and cooled. In homes heated by natural gas, monthly natural gas billing data were also collected. The Princeton Scorekeeping Method (PRISM) was used to determine annual energy consumptions and savings, all normalized to long-term weather conditions.

In the demonstration group, both EASY and the Weatherization Assistant (NEAT for site-built single-family homes and MHEA for mobile homes) were run on 14 of the 18 houses so that the recommendations from the audits could be directly compared (see Table ES.1). Overall, EASY recommended the same basic measures that NEAT/MHEA recommended (infiltration reduction, attic insulation, and wall insulation)[1], but then recommended additional measures that NEAT/MHEA did not determine to be cost effective (window treatments, door replacements, and air conditioner replacements). Thus, NEAT/MHEA recommended a reduced investment in most homes.

[1] Floor insulation was not recommended by either audit because the local agencies could not insulate the floors in the study houses.

Table ES.1. EASY and NEAT/MHEA recommendations in the 14 demonstration houses

Weatherization measure	EASY recommendations		NEAT/MHEA recommendations	
	No. of homes	Percent of homes	No. of homes	Percent of homes
Infiltration reduction	14	100%	14	100%
Attic insulation	14	100%	14	100%
R-19	1	7%	11	79%
R-26	1	7%	0	-----
R-30	12	86%	0	-----
R-38	0	-----	3	21%
Wall insulation	8	57%	8	57%
Window replacement	8	57%	0	-----
Storm window	8	57%	0	-----
Door replacement	10	71%	0	-----
Air conditioner replacement	10	71%	1	7%

Table ES.2 summarizes the frequency that measures were actually installed in 31 of the 35 study homes for which measure installation information was available.[2] In most homes, health, safety, and repair items were installed in addition to those measures that the audits recommended based on cost effectiveness. In a few cases, measures recommended by EASY or NEAT/MHEA could not be installed (e.g., in two site-built homes, ceilings could not be insulated because of the presence of knob-and-tube wiring).

The mix of measures installed in the 31 field test homes were different than those installed in houses located in the hot-climate region in 1989 when the last national evaluation of the Program was performed. Five measures that were performed more frequently in the study homes compared to the homes weatherization in 1989 are:

- Blower-door-guided infiltration work—performed in 97% of the study homes but in only 1.4% of the houses in 1989.
- Attic insulation—performed in 74% of the study homes but in only 43.0% of the houses in 1989.
- Wall insulation—performed in 39% of the study homes but in only 1.1% of the houses in 1989.
- Measures involving the space-heating system—replacement units installed in 16% of the study homes compared to any space-heating system work being performed in only 3.7% of the houses in 1989.
- Replacement air conditioners—installed in 68% of the study homes but in essentially none of the houses in 1989).

Table ES.2 also shows the distribution of average costs for measures installed in the 31 houses. The total cost of $5,053 was evenly distributed among three types of measures: those that both EASY and NEAT/MHEA determined would save energy and be cost effective ($1,653); those that could save energy but were cost effective only by EASY's estimates but not NEAT/MHEA's estimates ($1,732); and health,

[2] The measures installed in the standard procedures group and demonstration group were about the same, so the groups were combined. The local agencies used EASY and followed their standard auditing procedures to select the weatherization measures that were installed in the standard procedures group. The auditors also selected additional health, safety, and repair items that were installed. In the demonstration group, ORNL developed weatherization recommendations for each house based on using NEAT for site-built single-family homes and MHEA for mobile homes. A modified version of ORNL's recommended measures were then installed after input was received from the state and the local weatherization agencies. Measures that NEAT/MHEA did not recommend based on their cost effectiveness (i.e., window replacements, door replacements, and air conditioner replacements) were still installed in some homes based on this input. Health, safety, and repair items were also installed.

safety, and repair items that neither of the audits recommended based on energy savings and cost-effectiveness considerations ($1,668). It is clear that making housing repairs, improving quality of life, and ensuring comfortable and safe indoor temperatures are important elements of Texas' overall program, which must be balanced against improving energy efficiency and reducing energy expenditures.

Table ES.2. Measure installation frequency and average cost for 31 study homes.

Measure type	Measure installation frequency		Average cost
	No. of houses	Percent	
Cost effective by both NEAT/MHEA and EASY:			
Infiltration reduction	30	97%	$746
Attic insulation	23	74%	$618
Wall insulation	12	39%	$289
Subtotal			$1,653 (33% of total)
Cost effective by EASY only:			
Window replacements	14	45%	$215
Storm windows	12	39%	$410
Door replacements	25	81%	$475
Air conditioner replacements	21	68%	$632
Subtotal			$1,732 (34% of total)
Health, safety, and repair:			
Heater replacements	5	16%	$383
Health and safety measures			$394
Repairs			$891
Subtotal			$1,668 (33% of total)
Total, all measures			$5,053

The measures installed in the study houses exemplify how the Program's two goals of making cost-effective energy-efficiency improvements and improving health and safety can be in conflict. Broken air conditioners were replaced with new units in some of the study homes. Although such replacements improve the health of the occupants by improving the indoor temperatures of the home during the summer and possibly reducing mold and mildew problems, it is likely that their use will result in an increase in energy use and expenditures rather than a decrease. Similarly, installing replacement air conditioners with increased cooling capacity and replacing space heaters that were not working or were unsafe to use, as was done in many study homes, is more likely to increase energy consumption than to reduce it. When little energy is being used because of inadequate or broken equipment, there is little opportunity to reduce energy use by installing additional energy-efficient equipment.

Energy audits like NEAT/MHEA and EASY provide recommendations on measures that should be installed that are based only on considerations of cost-effective energy savings. Judgments based on more than simple cost effectiveness are needed to guide the selection of health, safety, and repair measures, but no automated tools like energy audits are available to provide such guidance.

In 17 of the 18 demonstration homes, the pre-weatherization heating and cooling energy consumptions estimated by NEAT and MHEA were compared to actual consumptions.[3] Before weatherization, most houses used less heating and cooling energy than NEAT and MHEA predicted. For space heating, the

[3] Data were not available for one demonstration home, and comparable results are not available from EASY.

ratio between actual and predicted energy consumption for 11 of the 17 houses were between 0.5 and 1.2, and averaged about 0.75. This is consistent with other studies of NEAT and MHEA which found that they over predicted, on average, pre-weatherization space-heating energy consumption by between 10-35%. Several energy-use patterns were observed from analysis of the pre-weatherization data that help explain why energy consumptions and energy savings estimated by energy audits are less than actual. The study found that not all houses are maintained at the fixed temperatures often assumed in energy audits during the winter and summer. First, some houses were not heated during cold weather or were not cooled during hot weather part of the time during the pre-weatherization period. Second, in other homes, energy-use patterns of other appliances suggested that the occupants were absent from these houses for extended periods. Third, space heaters and window air conditioners are not always able to condition the entire floor area of a home. Fourth, in some homes before weatherization, the air conditioning system did not have sufficient capacity to keep the house at the desired temperature during the hottest part of the day.

These energy-use patterns suggest that the accuracy of NEAT and MHEA (and audits in general) could be improved if the audits were programmed to account for the actual behaviors that occur in the homes.[4] Alternatively, energy-saving predictions could be adjusted based on a comparison of actual to predicted pre-weatherization energy consumption as the actual pre-weatherization consumption includes the effects of house-specific indoor temperatures, occupancy, etc.[5] Two issues arise as audits are made more accurate by accounting for house-specific occupant and equipment behaviors:[6]

- Basing audit recommendations on current occupant and equipment behaviors could increase audit accuracy for the present occupants, but it could result in less than optimum results for the long term when other people occupy the house.

- The resulting program may be looked upon as unfair because such a program would install (a) more measures in homes that had heating and cooling equipment capable of conditioning their entire home and fewer measures in homes that had inoperative or non-existent equipment, and/or (b) more measures in homes whose occupants were not careful about energy consumption and fewer measures in homes whose occupants practiced energy conserving behaviors or lacked the means to heat or cool the house to more comfortable temperatures.

Twenty-four homes had sufficient energy consumption data that could be analyzed with PRISM to determine their energy savings from weatherization (see Table ES.3). Savings averaged 140 therms for gas-heated homes and 1,800 kWh in electrically heated homes. The average electricity savings of 1,100 kWh in the gas-heated homes, which mainly reflects the effect of weatherization on space cooling, is not statistically significant. These results are consistent with previous studies of houses in hot climates that showed significant gas savings, but cooling savings that were not statistically significant.

Compared to the results from the 1989 national evaluation of the Program, the results show that improved savings have been achieved in the study homes. From the 1989 evaluation, the gross annual energy savings for homes heated by natural gas in the hot climate was 102 therms, but 137 therms for the moderate climate (electricity savings in gas-heated homes were not measured in the 1989 evaluation). Similarly, in electrically heated homes, the savings was 307 kWh in hot-climate homes and 939 kWh in moderate-climate homes.

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[4] NEAT and MHEA already allow the auditor to enter the actual amount of floor area that is heated or cooled.

[5] NEAT and MHEA already provide a simple, optional means for adjusting energy savings estimates based on how well their prediction of pre-weatherization energy use compares to actual energy use.

[6] The long-term perspective has merit when the long lifetime of most weatherization measures (15 to 20 years) is considered and the fact that houses often change occupants within 5 years.

Table ES.3 Annual energy savings

House type and fuel	Annual energy savings	95% confidence interval
Gas-heated homes (11):		
Natural gas	140 therms	90 to 190 therms
Electricity[a]	1,100 kWh	-870 to 3,100 kWh[b]
Electrically heated homes (13):		
Electricity[c]	1,800 kWh	0 to 3,600 kWh

[a] Electricity savings should mainly reflect the effects of weatherization on space cooling.
[b] Electricity savings are not statistically different from zero at a 95% confidence level.
[c] Savings reflects the effects of weatherization on both space heating and space cooling.

To study the impact of air conditioner changes on space-cooling electricity savings, annual electricity savings for homes that received air conditioner changes were compared to homes that had no cooling system changes. There appeared to be a trend toward larger electricity savings in houses that had more investment in air conditioners for the gas-heated houses, but no such trend was evident for the electrically heated homes. For both sets of homes, savings were higher in homes receiving air conditioners in which the capacity increased rather than staying the same, which is opposite of what one would expect.

Indoor temperature data were analyzed to determine how indoor temperature (and hence comfort) changed in response to weatherization and specifically to changes in air conditioning and heating equipment. Overall, it appears that weatherization increased indoor comfort levels, although substantial comfort improvements may be occurring in just some houses. It was not clear from the analyses that these improvements were attributable specifically to heating or cooling system changes. Specifically, the study found that:

- During the summer, the average indoor temperature for 26 study houses with available data was about 75°F to 76°F before weatherization and was 1.8°F cooler following weatherization (with a 95% confidence interval of 2.7 to 0.9°F), although this average change was strongly influenced by a few houses that had large decreases in indoor temperature.

- During the summer, the number of days with uncomfortably warm indoor temperatures decreased significantly after weatherization.

- During the winter, the average indoor temperature of 21 study houses with available data increased by 0.9°F, with a 95% confidence interval of 0.1 to 1.7°F.

Conclusions reached from the study include:

- Improved Program designs and the use of energy audits such as EASY and NEAT/MHEA resulted in better weatherization measures being installed (use of blower doors to guide the infiltration work, more frequent installation of attic insulation, and installation of wall insulation) in the study homes and improved space-heating savings performance compared to the Program as implemented in the hot climates in 1989.

- Weatherization of the study homes led to more comfortable indoor temperatures.

- The poor physical condition of the study homes and their resulting need for significant health and safety measures and substantial repairs creates a key policy dilemma for Texas and other hot-climate states; namely, how to balance expenditures between installing cost-effective weatherization measures and performing health, safety, and repair items.

- A second key policy dilemma highlighted by the study for hot-climate states is that health, safety, and repair items can adversely affect energy savings, which further complicates the decision process that states and agencies must undertake. New air conditioning or heating equipment that contributes to an increase in capacity (because the existing unit was inoperative or of a lower capacity than the new unit) may lead to increased air conditioning or space-heating energy consumption.

- NEAT/MHEA identify a different set of weatherization measures that are cost effective compared to EASY.

- NEAT's and MHEA's pre-weatherization space-heating and air-conditioning energy consumption estimates were usually significantly greater than measured values, which can lead to over predictions of energy savings for measures and recommendations of measures that are not cost effective.

- Several occupant and equipment-related behaviors observed in the field test homes help explain why audits may over predict energy consumptions and savings and why air-conditioning electricity savings are difficult to measure.

- To improve audit accuracy, the specific occupant and equipment behaviors before weatherization would need to be entered into and used by the audit, and/or audit predictions would need to be adjusted to the actual pre-weatherization energy use of the house to account for the home's unique occupant and equipment behaviors. However, in doing so, the weatherization based on current occupant behavior may be less than optimal in the long run, when other people occupy the home, and the resulting Program may be viewed as unfair.

Recommendations based on the study include:

- States in hot climates should be encouraged to select from an expanded list of measures using advanced audits or other techniques as exemplified in this field study. These programs should be evaluated and comfort improvements should be assessed.

- Further studies examining the benefits obtained from air conditioner measures is warranted. These studies should address energy savings, comfort improvements, and the impact of capacity increases on energy savings and comfort.

- Guidelines should be developed for the hot-climate states on how to (a) balance the objectives of saving energy, improving health and safety, and addressing repair issues, and (b) select repair items.

- Studies should be performed and guidance should be developed on whether Program objectives are best met by weatherizing houses based on actual or typical energy use, and current or long-term occupant behavior.

- Weatherization measures should be identified and tested that can improve the livability and comfort of hot-climate houses that have very low energy use and/or are not heated or cooled to normal, comfortable temperatures without increasing their energy consumption.

ABSTRACT

A field test involving 35 houses was performed in Texas between 2000 and 2003 to study the response of low-income homes in hot climates to weatherization performed as part of the U.S Department of Energy Weatherization Assistance Program and to investigate certain methods to improve weatherization performance. The study found that improved Program designs and the use of advanced energy audits resulted in better weatherization measures being installed (use of blower doors to guide the infiltration work, more frequent installation of attic insulation, and installation of wall insulation) in the study homes, improved space-heating savings performance compared to the Program as implemented in the hot climates in 1989, and more comfortable indoor temperatures. Two key policy dilemmas for Texas and other hot-climate states were highlighted by the study; namely, how to balance expenditures between installing cost-effective weatherization measures and performing health, safety, and repair items, and that health, safety, and repair items can have an adverse impact on energy savings, which further complicates the weatherization decision process. Several occupant and equipment-related behaviors were observed in the field test homes that help explain why audits may over predict energy consumptions and savings and why air-conditioning electricity savings are difficult to measure. Based on this study, it is recommended that states in hot climates be encouraged to select from an expanded list of measures using advanced audits or other techniques, and further studies examining the benefits obtained from air conditioner measures should be performed. In addition, guidelines should be developed for the hot-climate states on how to (a) balance the objectives of saving energy, improving health and safety, and addressing repair issues, and (b) select repair items.

1. INTRODUCTION

Under the sponsorship of the U.S. Department of Energy (DOE), the Weatherization Assistance Program (the Program) has weatherized approximately six million low-income residences nationally since its inception in 1976. This federally funded program, which is implemented by state and local agencies in all 50 states and the District of Columbia, is designed to increase residential energy efficiency, thereby lowering energy costs for low-income occupants and improving their health, safety, comfort, and quality of life.

A number of evaluations of the Program both at the national level (Brown et al. 1993) and state level (Berry 1997, Schweitzer and Berry 1999, Berry and Schweitzer 2003) have reported space-heating energy savings attributable to the Program that are lower in hot-climate households than in cold-climate households. Space-heating energy savings in hot-climate homes are typically less than half as much as the amount measured in cold-climate homes when expressed in physical units (such as in hundreds of cubic feet of natural gas). When expressed as a percentage of the pre-weatherization space-heating energy use or pre-weatherization energy use of the primary space-heating fuel, the savings are still less in hot-climate homes but more similar because of the lower pre-weatherization fuel consumption for space heating in hot-climate homes.

Previous program evaluations in hot climates based on analyzing monthly utility bills have produced puzzling results concerning cooling savings attributable to weatherization. Although several such studies have been able to measure the space-heating savings occurring in hot-climate dwellings, similar studies using monthly electric billing data to measure electric cooling savings have detected no significant effects.

DOE sponsored a study by Oak Ridge National Laboratory (ORNL) in Texas to investigate the response of low-income homes in hot climates to weatherization and certain methods to improve weatherization performance. Specifically, the study was performed to:

- Compare measures recommended and installed following the EASY audit as used by Texas and the DOE-sponsored Weatherization Assistant, which is a more comprehensive auditing approach;

- Measure the space-heating and space-cooling energy consumption in homes to be weatherized and the savings achieved in a sample of weatherized homes; and

- Gain insight into why energy use and savings for heating and cooling are lower than expected, as previously observed in studies of hot-climate weatherized homes.

2. DESCRIPTION OF THE TEXAS FIELD EXPERIMENT

2.1 TEXAS FIELD EXPERIMENT DESIGN

The Texas Field Experiment was initiated in late 2000 and was performed using homes selected from two weatherization agencies in southeastern Texas: Programs for Human Services (PHS) in Beaumont and Greater East Texas Community Action Program (GETCAP) in Nacogdoches (see Fig. 2.1). Beaumont, being near the Gulf Coast, is mild in the winter (1,447 annual heating degree days at base 65°F) and warm and humid in the summer (2,823 annual cooling degree days at base 65°F). The mean daily maximum ambient temperature is above 80°F during May through October, while the mean daily minimum ambient temperatures from December through February are below 50°F. The area around Nacogdoches is a little cooler than Beaumont. The average annual heating degree days for the Lufkin airport weather station is 1,900 and the average annual cooling degree days is 2,480. The mean daily maximum ambient temperature is above 80°F during May through October, so the cooling season in Nacogdoches is about as long as the Beaumont area. However, the heating season is likely a little longer than the Beaumont area because the mean daily minimum ambient temperatures are below 50°F from November through March.

Local agencies recruited 57 homes (both site-built single-family homes and mobile homes) for the field study between January and May 2001. About two-thirds of the houses selected were in the Beaumont and Port Arthur area. The remaining houses were about 100 miles inland in the communities of Trinity and Groveton, between the cities of Lufkin and Huntsville and near Nacogdoches.

Figure 2.1. Location of the two agencies that participated in the Texas Field Experiment.

Initially, only all-electric houses were to be selected for the study.[7] However, after several months of effort, homes heated by natural gas were allowed in the study when it became clear that there were not enough all-electric houses among the client population.[8] Thus, in the end, about 60% of the homes initially selected for the study were electrically heated and the rest were heated with natural gas.

A pre- and post-weatherization experimental design was used in the study. The pre-weatherization period for each house began between February and July 2001 once special equipment to monitor the electricity use and indoor temperature had been installed (see Sect. 2.3). The homes were weatherized between May and November 2002, with more than two-thirds of the homes getting weatherized between May and July 2002. Post-weatherization data were then collected through October 2003.

Two groups of homes were used in the field study: (a) homes that were weatherized following the recommendations of the Texas EASY audit and Texas' standard auditing procedures (the standard procedures group), and (b) homes (the demonstration group) that were weatherized based primarily on the recommendations of the DOE-supported Weatherization Assistant (Version 7) which includes the National Energy Audit Tool (NEAT) and the Manufactured Home Energy Audit (MHEA). These audits and how they were implemented are discussed in depth in Sect. 2.2. Although an original intent of the field study had been to compare the energy savings achieved under these two approaches, this analysis was not performed because, in the end, similar measures were installed under both approaches (see Sect. 4) and attrition reduced the number of homes in each group to the point that statistically valid comparisons could not be made. Therefore, analyses of energy consumptions and savings, indoor temperatures, and load profiles were performed for the two groups as a whole rather than individually, with results provided in Sects. 5 and 6.

The houses were assigned to one of these two groups in February 2002. This was done by matching houses with similar characteristics to the maximum extent possible and then randomly assigning one house from each matched pair to the standard procedures group and the other to the demonstration group. The following characteristics were considered in the following priority to create the matched pairs: geographic location (Beaumont, Groveton, Orange, Silsbee, Trinity, and all other cities); house construction (single-family or mobile home); primary space-heating fuel (electricity and natural gas); type of cooling equipment; type of heating equipment; and floor area. An analysis verified that the two experimental groups were very similar in all of their energy-related characteristics, including their average floor area, number of occupants, pre-weatherization air leakage measurements, and number of room air conditioners per house.

Only 35 of the original 57 houses remained in the field test through the post-weatherization data collection phase (17 standard procedures houses and 18 demonstration houses). Of the 22 homes dropped from the study, the occupants had moved out in more than half due to deaths, hospitalizations, nursing home stays, divorces, and other reasons. Other reasons why homes were dropped from the study included disruptions in the electric service in several homes, a fire that burned one house down, a schizophrenic occupant at one house who destroyed the data recorders, and inadequate wiring at one house that presented safety and liability concerns. Problems with insufficient data collected both before and after weatherization caused additional houses to become unsuitable for the analyses presented in Sects. 5 and 6 (see Sect. 2.4)

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[7] All electric homes were initially preferred because a complete picture of household energy use by appliance was originally desired and the special monitoring equipment that was to be installed in each house could not monitor natural gas use.

[8] Only about 11% of client homes in the PHS and GETCAP service areas were heated with electricity, with most of the rest being heated with natural gas.

The following data were collected on each of the study homes:

- Information needed to perform an EASY audit, which was also used to select the matched pairs of homes;
- Information needed to run NEAT or MHEA (collected only in those homes assigned to the demonstration group);
- Information documented in the Building Weatherization Report (BWR) for each house (e.g., measures installed and their costs);
- Occupant responses to questions;
- Information collected by ORNL staff during field visits;
- Monthly natural gas utility billing data on all homes heated by natural gas;
- Submetered whole-house electric consumption; and
- Indoor temperature.

2.2 ENERGY AUDITS

2.2.1 The Texas EASY Audit

The EASY audit is a computerized audit that was used by the State of Texas to identify recommended weatherization measures for Program homes at the time the field study was performed. Auditors use the software to draw a plan of the dwelling that is being audited. Auditors place objects (e.g., doors, windows, space-heating equipment, air conditioners, water heaters) on the plan, specify initial values for these house components (e.g., envelope R-values, operating efficiencies, shading, orientation, blower door readings), and then enter target values for weatherization measures they wish to consider for objects that have been included on the drawing (e.g., attic R-value, final blower door reading, efficiency of a new furnace). EASY then performs calculations using heating and cooling degree days for the specific location of the house to estimate the energy savings and cost effectiveness for the measures requested. Annual heating and cooling costs based on the client’s utility bills are also entered, although they are only used to adjust the estimated savings for space-heating system and air conditioner replacements.

2.2.2 The Weatherization Assistant

The Weatherization Assistant is a family of easy-to-use but advanced energy audit computer programs that identify the cost-effective energy-efficiency retrofit measures for a home after taking into account local weather conditions, retrofit measure costs, fuel costs, and specific construction details of the home. The Weatherization Assistant serves as the umbrella program for NEAT for site-built single-family homes and MHEA for mobile homes.

NEAT and MHEA guide the user through the process of entering data on the home that describe the characteristics of the home (e.g., envelope dimensions and R-values, air leakage rate), its heating and cooling systems (e.g., types and operating efficiencies), and base load equipment (e.g., refrigerators, water heaters, lighting in need of retrofit). NEAT and MHEA use engineering calculations and weather data from one of 216 weather cities in the U.S. to compute the annual heat loss and heat gain of the home, and the annual space-heating and space-cooling energy consumption required to keep the home at a specific thermostatic set point. Both programs calculate heat loss and heat gain on a monthly basis using a variable-base degree-day method and ten-year average weather data for the selected city. The amount of solar energy absorbed by a home and the typical amount of heat generated inside a home by people and their refrigerators, water heater, other appliances, and lights are considered in the computations. NEAT and MHEA also compute the energy consumption of selected baseload uses (water heating, refrigerators, and lighting in need of retrofit) if desired.

NEAT checks the applicability of 34 building envelope, space-heating and space-cooling system, and baseload energy-efficiency measures to the specific home being audited, while MHEA checks the applicability of 31 measures. These measures include air and duct leakage reduction, envelope insulation, window replacements and other treatments, space-heating and space-cooling equipment replacement and tune-up, replacement refrigerators, water heater tank and pipe insulation, replacement lighting, and more. Both programs calculate an energy savings and discounted savings-to-investment ratio (SIR) for each applicable measure after interactions between measures have been accounted for. User-defined energy efficiency measures can also be entered and evaluated. The SIRs are calculated using fuel costs and installation costs representative of the home and agency as input by the user, as well as measure lifetimes appropriate for each measure.

Finally, NEAT and MHEA produce a prioritized list of cost-effective weatherization measures customized for the dwelling being evaluated. The output includes estimates of the dollar value for the projected energy savings, SIRs, installation costs, a list of the quantities of the major materials necessary to perform the recommended weatherization retrofits, and design heating and cooling loads needed to size any replacement equipment. If desired, NEAT and MHEA can adjust their estimated energy savings based on actual utility consumption data and develop a second list of recommend energy efficiency measures.

2.2.3 Audit Comparisons

There are several primary differences between EASY and NEAT/MHEA (based on the versions used at the time of the field study):

- NEAT and MHEA evaluate a greater number of weatherization measures than EASY (e.g., refrigerator replacement, lighting retrofits).
- NEAT and MHEA automatically check on the applicability and cost effectiveness of a library of weatherization measures on each house audited, while EASY only considers measures that the auditor specifies.
- NEAT and MHEA automatically determine the optimum amount of insulation to install, while EASY only considers the level of insulation specified by the auditor.
- NEAT and MHEA account for the interaction between measures before developing its final list of recommended measures, while EASY does not.

2.2.4 Implementation of the Audits

The weatherization measures installed in the standard procedures group (17 houses) were selected by the local weatherization agencies following their standard auditing procedures and using the EASY audit. These procedures included identifying energy-efficiency measures based on their cost effectiveness, performing blower-door-guided infiltration to reach specific air-leakage targets, and performing extensive health, safety, and repair items.

The demonstration group (18 houses) was audited both by ORNL using the Weatherization Assistant (NEAT or MHEA) and by the local weatherization agencies using EASY and following their normal auditing procedures. The weatherization measures installed in the demonstration group were selected primarily by ORNL based on the recommendations from the Weatherization Assistant audit, although the local weatherization agencies and the state (i.e., TDHCA) also provided input into the selection process, especially regarding health, safety, and repair items that they felt needed to be performed in these homes.

The same weatherization measures were considered for installation in the standard procedures group and the demonstration group with two exceptions. In the demonstration group, two new weatherization measures were evaluated as part of the ORNL auditing process that were not currently part of Texas' Program but were expected to improve Program performance in hot climates: refrigerator replacement and replacement heat-pump water heaters. These are discussed in more detail in Sect. 4.2.

2.3 ELECTRIC AND INDOOR TEMPERATURE METERING

The Nonintrusive Appliance Load Monitoring System (NIALMS) produced by Enetics[9], Inc. was installed in each of the study homes to submeter the electricity consumption of the homes. NIALMS is a whole-house electric end-use monitoring system that allows the collection of appliance-specific load data without entering customer homes or installing meters on specific appliances. The system also provides the capability to monitor indoor temperature.

The NIALMS system uses a single-point electric end-use disaggregation (SPEED) data recorder, which is installed between the utility electric meter and the meter base, to record data and then periodically send information it has collected to a central server by telephone-modem. The recorder samples the incoming current and voltage (including phases) 2,000 times per second. The SPEED meter identifies changes in load and records and stores the date and time of each change along with voltage, current, and real and reactive power. At the server, the analyst uses an Enetics software package, called Analysis Station, to analyze the data. With Analysis Station, the NIALMS system is capable of disaggregating total electricity usage into separate appliance loads and reporting the energy use of each appliance at 15-minute intervals.[10] The NIALMS software uses transitions from one state of power consumption to another to determine whether an appliance is on or off, and it matches load characteristics to a library of appliance signatures to calculate the loads induced by the active appliances.

With an accessory temperature monitor that plugs into an ordinary wall electrical outlet, the NIALMS system can also record indoor temperature at one location. For the field study, one temperature monitor was installed in each house, typically in a living or family room that the installer believed was where the occupants spent most of their waking hours. The indoor temperature data were recorded at the same intervals as the electricity consumption data (every 15 minutes). One limitation of the indoor temperature data is that a single indoor temperature monitored in a house may not accurately reflect the temperatures of other parts of the house, especially in the houses that were not centrally heated and cooled.

Although software is used to resolve the loads of the most important electrical appliances, it was found during the field study that the process can be very labor intensive. To achieve accurate results, an analyst must perform a significant amount of quality control on the primary data, closely inspect NIALMS results appliance-by-appliance, develop customized appliance models for complex appliances, and make corrections where needed. Difficulties included:

- The transitions from one state of power consumption to another can be similar for similar appliances. For instance, electric water heaters and large electric space heaters can sometimes look alike to NIALMS.

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[9] The prototype for NIALMS was originally developed by the Massachusetts Institute of Technology in the 1980s. The mature technology is now sold exclusively by Enetics, Inc., 830 Canning Parkway, Victor, NY 14564-8940. http://www.enetics.com.

[10] NIALMS was field tested by the Electric Power Research Institute (EPRI) and seven utility partners in the mid-1990s. The EPRI report on this field test showed that NIALMS is 90−95% accurate for most appliances.

- Some appliances have multiple components. For example, central air conditioners have a compressor, a fan to distribute the air in the house, and a second fan to cool the condenser. Because the fans and compressors do not go on and off at the same time, NIALMS sometimes fails to detect a transition from off to on or on to off.

- Some appliances operate at multiple states or modes. For example, refrigerators operate in three modes: idling while the interior temperature is at the desired level, cooling to lower the interior temperature, and defrosting. NIALMS is sometimes confused by transitions between these states.

- Circuit breakers in houses with inadequate wiring would frequently open when more than one appliance was on at the same time.

The data collected by the NIALMS system were primarily used to determine total daily electricity consumption and daily average indoor temperature for each house. These parameters were easy to generate from the SPEED data without building appliance models, and were needed for subsequent analyses. The difficulties described above prevented disaggregated electric loads from being determined in each house so that energy savings could not be attributed to specific weatherization measures such as refrigerators, electric water heaters, or air conditioners. However, appliance electricity consumptions were analyzed in some homes as part of this study to provide useful insight into what was happening in some of the houses.

Another problem that occurred with the data collection system was that electricity and especially telephone service shut-offs at the houses disrupted the communication of collected data. This led to insufficient data being collected before and/or after weatherization for some houses for the analyses performed in Sects. 5 and 6.

2.4 ENERGY CONSUMPTION AND SAVINGS ANALYSES

The Princeton Scorekeeping Method (PRISM, Fels et al. 1995) was used to determine annual pre- and post-weatherization energy consumptions and savings, all normalized to long-term weather conditions. In homes heated by natural gas, monthly natural gas utility billing data were analyzed using PRISM's heating-only model to determine the annual pre-weatherization space-heating energy consumption of each house (i.e., the space-heating portion of the natural gas consumption) and the annual natural gas energy savings of each house due to weatherization. In addition, total daily electricity consumptions determined by the SPEED/NIALMS monitoring were analyzed using PRISM's cooling-only model to determine the pre-weatherization space-cooling electricity consumption of each home and the whole-house electricity savings in each of these homes. Although this electricity savings includes changes in baseload consumption before and after weatherization, it principally reflects changes in air conditioning electricity consumption. In homes heated by electricity, total daily electricity consumptions determined by the SPEED/NIALMS monitoring were analyzed using PRISM's heating-and-cooling model to determine pre-weatherization space-heating and space-cooling electricity consumptions in each home as well as the annual whole-house electricity savings of the homes. This savings includes both changes in space-heating and space-cooling electricity consumptions. The actual weather data needed by PRISM to perform the analyses and normalizations (the median of the daily maximum and daily minimum) were obtained from the National Oceanographic and Atmospheric Administration (NOAA).

In its traditional heating-only model, PRISM determines a weather-adjusted annual index of fuel consumption, termed the normalized annual consumption (NAC), for each period (i.e., the pre-weatherization period and the post-weatherization period). PRISM also splits the NAC for the fuel being analyzed into two components and calculates values for these: the normalized annual heating consumption (NAHC) and the baseload energy consumption. NAHC represents the part of NAC that fluctuates with changes in outdoor temperature, while the baseload energy consumption represents the part of NAC that stays constant regardless of outdoor temperature variations. For each period, NAHC and baseload energy consumption (and to a lesser extent NAC) are dependent on the heating reference temperature (or balance point temperature) used within PRISM to calculate heating degree days. The heating reference temperature represents the outdoor temperature below which heating fuel is required for a home. PRISM is typically allowed to vary the heating reference temperature in each period until the best statistical model is achieved; the heating reference temperature is then reported along with the other estimators already discussed for each period. Once the NAC is calculated for each period, the normalized annual savings (NAS) is then calculated by subtracting the NAC for the post-weatherization period from the NAC for the pre-weatherization period.

In its cooling-only model, PRISM establishes a cooling reference temperature to calculate cooling degree days and determines a NAC and a normalized annual cooling consumption (NACC) that is similar to NAHC. In its heating-and-cooling model, both heating and cooling reference temperatures are established, heating and cooling degree days are used, and NAC along with NAHC and NACC are determined.

The NAC is the most robust estimator produced by PRISM and was used to calculate the energy savings presented in Sect. 6.1. Its value is fairly independent of the reference temperature(s), whereas NAHC, NACC, and the baseload energy consumption are sensitive to the reference temperature(s) chosen. Seasonal variability of appliances, lighting, water use, water temperatures, solar gains, and other factors also interfere with the calculations and interpretations of NAHC, NACC, "baseload" energy consumption, and even the reference temperature(s), but have relatively little impact on NAC. There is some belief that PRISM tends to overestimate NAHC and underestimate the baseload energy consumption because weather-dependent and/or seasonal baseload energy consumption gets integrated into the weather-dependent NAHC.

Although NAHC and NACC are less robust estimators than NAC, NAHC and NACC are the estimators used in the analyses presented in Sect. 5.1 to establish actual pre-weatherization space-heating and space-cooling energy consumptions. NEAT and MHEA estimate annual pre-weatherization space-heating and space-cooling energy consumptions rather than annual whole-house fuel use; therefore, NAHC and NACC rather than NAC are conceptually equivalent to NEAT's and MHEA's estimates.

The weather period typically used in PRISM to calculate the annual consumptions was also used in this study; namely, the period spanning January 1, 1980 through December 31, 1991. NEAT and MHEA base their estimates on a Typical Meteorological Year (typically called TMY weather data) as compiled by NOAA, which represents typical weather conditions as they occurred between 1948 and 1980 (National Climatic Data Center 1981). This older, longer period was not used in PRISM because the needed data were unavailable. However, it is doubtful that the findings presented in Sect. 5.1 comparing NEAT and MHEA estimates to measured values were significantly affected because different weather years were used for the normalization.

While PRISM is well accepted in the evaluation field, it has a number of known limitations. One of these limitations is that PRISM can determine the NAC (or NAHC and NACC) only if there is an adequate linear model fit between energy consumption and heating (and/or cooling) degree days during the period in question, and both periods if a savings is desired. Another limitation of PRISM is that the differences in NAC, NAHC, and NACC provide very little insight into why the measured savings were, or were not, similar to the expected savings.

3. HOUSE CHARACTERISTICS

Detailed descriptive information was obtained on 35 of the study homes: 24 site-built single-family houses and 11 mobile homes. The house descriptions presented in this section are based on audit information collected by the local agencies in all 35 houses and audit information collected by ORNL on the 18 demonstration group houses (14 site-built houses and 4 mobile homes). The level of detail available on the houses audited by ORNL is greater than on those that were audited only by agency staff.

3.1 SITE-BUILT SINGLE-FAMILY HOUSES

3.1.1 Size

The floor areas of the 14 site-built houses visited by ORNL ranged from about 750 to 1,600 ft^2 and averaged about 1,150 ft^2.[11] Four of the 14 houses had central heat and air conditioning; these houses were a little bigger, having an average floor area of about 1,330 ft^2. Ten of the houses had additions, garages, or porches that had been enclosed and converted into enclosed living spaces. The floor area of 6 of the 10 additions ranged from 180 to 240 ft^2, while the area of the remaining 4 additions ranged from 380 to 500 ft^2.

3.1.2 Infiltration

The average pre-weatherization infiltration rate for the 24 site-built homes as measured by a blower door was 4,450 cfm at 50 Pa (one house with a blower door reading of 6,000 cfm at 25 Pa was excluded from this average). Values ranged from about 2,500 to 8,500 cfm at 50 Pa. In fact, only 2 of the 24 site-built houses had measured blower-door infiltration rates below 3,000 cfm at 50 Pa before weatherization.

The very high infiltration rates were usually due to a large hole in the ceiling. Several houses had a broken or missing attic access hatch (Fig. 3.1), an unsealed chase where heating and cooling ducts entered the attic (Fig. 3.2), or whole-house fan louvers that admitted large quantities of air during blower door testing. Other air leakage sites that were observed in the ceiling included a large leak where an unused water heater vent penetrated the ceiling and along the entire length of the joint between an addition and the original house. In addition, several houses had leaks through or around wall furnaces or window air conditioners.

3.1.3 Insulation

In the 14 site-built houses audited by ORNL, 6 houses had no ceiling insulation and 4 houses had 1 in. of insulation or less. Two of these houses had knob-and-tube wiring that prevented the agencies from considering adding insulation to them because of the potential fire hazard associated with covering this type of wiring with insulation. Of the 10 site-built houses that were not visited by ORNL, the local agencies reported that only one home had any ceiling insulation at all.

[11] The floor areas of the 10 site-built houses audited only by the local weatherization agencies ranged from 908 to 2,320 ft^2, with an average of 1,573 ft^2. These floor areas were not readily comparable to the areas reported for the 14 site-built houses that ORNL audited because the ORNL method of measuring houses led to consistently smaller areas than those reported by the agencies. For the 14 houses audited by both ORNL and the agencies, the average floor area of the houses estimated by the agencies was 1,510 ft^2 compared to ORNL's calculated average of 1,150 ft^2. Consequently, it appears that the 10 houses that were not audited by ORNL are similar in size to the 14 houses that were audited by ORNL, and that the average values and ranges reported for the 14 houses based on ORNL's measurements are representative of the 10 houses that ORNL did not audit.

Figure 3.1. Broken attic access hatch allows a high infiltration rate.

Figure 3.2. Unsealed equipment chase permits infiltration.

Only 4 of the 14 site-built houses audited by ORNL had wall insulation: 1 house with wood siding that had blown-in wall insulation and 3 houses with brick siding that had wall insulation installed at the time the houses were built. Of the 10 site-built houses audited only by local weatherization personnel, half had no wall insulation and half were reported to have R-9 wall insulation.

Of the 14 site-built houses ORNL visited, 2 had slab floors and all others had exposed floors (typically pier-and-beam construction). None of these houses had floor insulation. The local agencies did not report on the presence or absence of floor insulation in the remaining 10 houses because they considered the floors impractical to insulate (the agencies do not insulate slab floors, and the space under the houses with pier-and-beam construction is typically too shallow to allow weatherization personnel to work safely under them).

3.1.4 Space-Heating and Air Conditioning Systems

Of the 24 site-built houses, 6 were heated and cooled by central heat and air conditioning systems. Of those 6 homes, 4 were heated by electricity and the remaining 2 were heated by natural gas. The typical cooling capacity of the centrally cooled houses was 36,000 Btu/hour. The smallest central air conditioner had a capacity of 24,000 Btu/hour and the largest had a capacity of 42,000 Btu/hour. Of the 4 centrally heated and cooled houses audited by ORNL, 2 were originally built with central heat and air, the other 2 had central heat and air added later, and 1 also had a room air conditioner that was used to cool an addition that was inadequately cooled by the central system. Of 10 houses audited by local agency personnel, only 2 were heated and cooled by central systems (1 with electric heat and 1 with gas heat).

All of the 18 houses without a central cooling system had at least one window air conditioner. Most of these houses had 2 window air conditioners, but 2 houses had just a single window air conditioner, 3 houses had 3 window air conditioners, and 2 houses had 4 window air conditioners. The average total cooling capacity in these 18 houses was 17,000 Btu/hour, but the range was large. One house had only a single 5,000-Btu/hour unit, while another had three operational window air conditioners with a combined capacity of 36,000 Btu/hour. Several houses had window air conditioners installed that were no longer working. A few houses had previously used whole-house fans for cooling, but only one of those fans was still used by the occupants.

Of the 18 houses without central heat and air conditioning, 10 were audited by ORNL. Six of these were heated by gas and the other four were heated by electricity. In the 6 gas-heated homes, 5 were heated by room-sized gas equipment (primarily unvented gas space heaters) and 1 used only the gas range to heat the house. Some of the four houses heating with room-sized electric equipment had been heated with gas originally, but had converted to heating with portable electric space heaters in one or more rooms because the gas heaters no longer worked properly. One house had been built with a central heat pump system, but used a portable electric space heater and a window air conditioner because the heat pump system was broken.

3.1.5 Appliances

Of the 24 site-built homes, 11 (almost half) had electric water heaters even though only 8 (or one-third) of the houses had electric heat. In the gas-heated houses with electric water heaters, an electric water heater had been installed when the gas water heater had failed.

Most of the existing refrigerators in the houses were less than 9 years old and had a capacity of less than 20 ft^3. A program of replacing old refrigerators had been implemented by the electric utility serving this area during the past few years.

3.1.6 Repairs

Many items needing repair were observed while conducting the audits. Three houses had roofs that were in need of replacement (Fig. 3.3), including one house that had water damage from a roof leak (Fig. 3.4) and a plastic tarp covering the roof to prevent additional leakage. Several houses had windows that needed to be replaced or repaired (Fig. 3.5). Most doors were in adequate condition, but a few needed to be replaced (Fig. 3.6). Two heaters were in need of repair. Other repair items that were noted dealt with plumbing, electrical problems, exterior siding, interior drywall, and painting.

Figure 3.3. House with a roof in need of replacement.

Figure 3.4. Water damaged ceiling due to a leaking roof.

Figure 3.5. Weather damaged window in need of replacement.

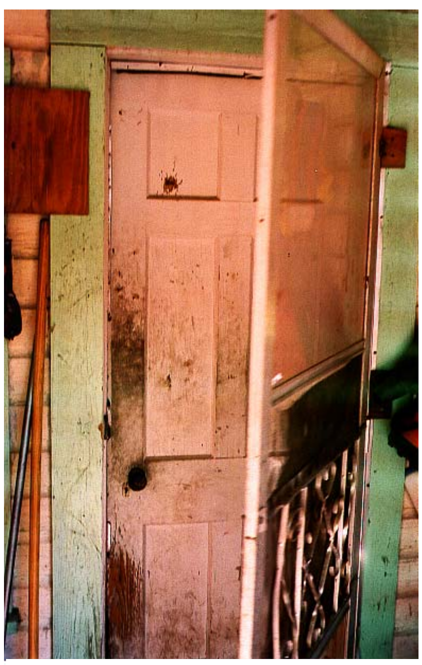

Figure 3.6. Door in need of replacement.

3.2 MOBILE HOMES

The floor area of the 11 mobile homes ranged from 784 to 1,320 ft^2. The most common mobile home floor area was 1,100 ft^2.

Pre-weatherization infiltration rates as measured by a blower door ranged from 2,000 to 4,650 cfm at 50 Pa.

The pre-weatherization R-values reported by the agencies for the ceilings ranged between R-4 (no cavity insulation) to R-17, with R-9 being the most common reported ceiling insulation value. Walls were reported to have insulation values in the range of R-4 (no cavity insulation) to R-10, with the most common wall insulation value being R-9. Floor insulation levels were not reported by the local agencies. Of the four mobile homes visited by ORNL, three had 2 to 3 in. of floor insulation and one had 6 in.

Most mobile homes are sold with central space-heating systems. In several mobile homes, these central space-heating systems had been abandoned in place or removed and replaced after the central systems failed. Four of the 11 mobile homes were heated with natural gas. All of the mobile homes had air conditioners. Four homes were equipped with central air conditioning systems while the other seven homes had window air conditioning units.

As with the site-built homes, many items needing repair were observed in the mobile homes. Roofs needing repair were observed in all but 1 of the 11 mobile homes. Water damaged floors were common. Of the 4 mobile homes that ORNL visited, 3 had areas of the floor that had been seriously damaged by water. Plumbing and electrical repairs were also noted.

3.3 COMPARISON OF STUDY HOMES TO OTHER HOT-CLIMATE AREAS

In an effort to understand the extent to which the household and energy use characteristics found in this study of south Texas homes might be applicable to homes in other hot climates, the characteristics of the study houses were compared with the characteristics of low-income houses in the Residential Energy Conservation Survey (RECS) in similar climates. The details of this comparative analysis are presented in Appendix A. The results show that there are many similarities between the study houses and low-income RECS houses in similar climates. For both mobile homes and single-family homes, average electricity use intensity (kWh/year/ft^2) is similar. Based on this analysis, there is no reason to suspect that the study houses are atypical of low-income homes in similar climates.

4. WEATHERIZATION MEASURES

4.1 COMPARISON OF AUDIT RECOMMENDATIONS

In the demonstration group, both EASY and the Weatherization Assistant (NEAT for site-built single-family homes and MHEA for mobile homes) were run on 14 of the 18 houses so the recommendations from the audits could be directly compared. Table 4.2 compares the recommended weatherization measures based on EASY to those based on NEAT and MHEA for these 14 houses.

Table 4.1. EASY and NEAT/MHEA recommendations in the 14 demonstration houses.

Weatherization measure	EASY recommendations		NEAT/MHEA recommendations	
	No. of homes	Percent of homes	No. of homes	Percent of homes
Infiltration reduction	14	100%	14	100%
Attic insulation	14	100%	14	100%
R-19	1	7%	11	79%
R-26	1	7%	0	-----
R-30	12	86%	0	-----
R-38	0	-----	3	21%
Wall insulation	8	57%	8	57%
Window replacement	8	57%	0	-----
Storm window	8	57%	0	-----
Door replacement	10	71%	0	-----
Air conditioner replacement	10	71%	1	7%

There were many similarities in the weatherization measures that were found to be cost effective by EASY and NEAT/MHEA. Both EASY and NEAT/MHEA recommended infiltration reduction in all 14 homes and wall insulation in 8 of the homes. In addition, both audits recommended that attic insulation be installed in all the homes, although NEAT/MHEA recommended that R-19 be added in most houses while EASY recommended R-30 for most homes because R-30 was the target value entered by the auditors. It should be noted that floor insulation was not recommended by either audit because the local agencies could not insulate the floors in the study houses (the agencies do not insulate slab foundations, the space under the houses with pier-and-beam construction was too shallow to allow weatherization personnel to work safely under them, and the agency staff were not yet trained in how to insulate the floors of a mobile home).

The primary difference between the recommendations made by EASY and NEAT/MHEA was that EASY recommended window treatments (i.e., window replacements and storm windows), door replacements, and air conditioner replacements in about 60−70% of the houses for each of these measures while NEAT/MHEA recommended no such measures (except for an air conditioner replacement in just one home).[12] Clearly, NEAT/MHEA determined that these measures were not cost effective while EASY determined they were.

The overall effect of these similarities and differences is that EASY recommended the same basic measures that NEAT/MHEA recommended, but then recommended additional measures that NEAT/MHEA did not. NEAT/MHEA recommended fewer measures and, hence, less total expenditure, per house than EASY. Put another way, NEAT/MHEA recommended a reduced investment in most

[12] NEAT does not evaluate the cost effectiveness of door replacements directly because, as stated in its Users Manual, they “are normally not cost-effective measures, based solely on heat conduction savings.”

homes, especially the amount of investment in air conditioner replacements, window and door replacements, and storm windows.

4.2 INSTALLATION FREQUENCY OF MEASURES

As discussed in Sect. 2.2.4, the local weatherization agencies used EASY and followed their standard auditing procedures to select the weatherization measures that were installed in the standard procedures group. The auditors also selected additional health, safety, and repair items that were installed. In the demonstration group, ORNL developed weatherization recommendations for each house based on using NEAT for site-built single-family homes and MHEA for mobile homes. A modified version of ORNL's recommended measures were then installed after input was received from TDHCA and the local weatherization agencies, especially concerning health, safety, and repair items.

Table 4.2 summarizes the frequency that measures were installed in 31 of the 35 study homes based on the BWRs prepared by the local agencies: all 17 standard procedures homes and 14 of the 18 demonstration homes for which BWRs were available. In most homes, health, safety, and repair items were installed in addition to those measures that the audits recommended based on cost effectiveness. In a few cases, measures recommended by EASY or NEAT/MHEA could not be installed (e.g., in two site-built homes, ceilings could not be insulated because of the presence of knob-and-tube wiring). Most importantly, in the demonstration group, measures that NEAT/MHEA did not recommend (see Table 4.1) based on their cost effectiveness (i.e., window replacements, door replacements, and air conditioner replacements) were still installed in some homes because of decisions made by the state and the local agencies that were based on criteria other than cost effectiveness (including comfort and safety).[13]

As previously mentioned in Sect. 2.2.4, two new retrofit technologies (refrigerator replacement and replacement heat pump water heaters) were considered for the demonstration-group homes in addition to having standard weatherization measures selected by NEAT and MHEA. These new technologies were not currently being used in the Texas Program but offered the possibility of improving Program performance in hot climates. As it turned out, neither technology was tested under this study. Due to a utility program, almost every house in the study already had a new refrigerator installed within the previous two years. ORNL installed heat pump water heaters in three demonstration-group houses in cooperation with another evaluation project being conducted by DOE. However, problems with the units or installations caused all three to be removed before enough time passed to evaluate their performance, indicating that the technology was not yet sufficiently developed for inclusion in the Program.

In the end, the measures installed in the two groups of homes were fairly similar. This occurred because local agencies and the state requested additional measures be installed in the demonstration homes to address equipment operation and other repair issues, and because no new technologies were installed in the demonstration homes. As a result, analyses presented in the remaining sections of this report only deal with both groups of house as a whole and do not try to make comparisons between the two groups.

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[13] NEAT and MHEA did not find any window replacement, storm window installations, or door replacements that would be cost effective in the demonstration-group houses. However, after receiving input from the local agencies and the state (primarily on the condition of the windows and doors and the need to replace them to be consistent with their program philosophy), windows and doors were replaced in eight houses each. Similarly, NEAT recommended an air conditioner replacement in only one demonstration-group home, but nine such homes received new air conditioners after the agencies and state overrode NEAT and MHEA's recommendations after factoring in the need for an air conditioner replacement based on its operating (or non-operating) condition, the possible energy savings from such a replacement, and possible health and comfort improvements.

Table 4.2. Frequency that measures were installed in the study homes

Measure type	Standard procedures group (17 houses)		Demonstration group (14 houses)		All houses (31 houses)	
	No. of houses	Percent	No. of houses	Percent	No. of houses	Percent
Infiltration reduction	16	94%	14	100%	30	97%
Attic insulation	10	59%	13	93%	23	74%
Wall insulation	4	24%	8	57%	12	39%
Window replacement	6	35%	8	57%	14	45%
Storm windows	12	71%	0	—	12	39%
Door replacement	17	100%	8	57%	25	81%
Air conditioner replacement	12	71%	9	64%	21	68%
Space heater replacement	3	18%	2	14%	5	16%
Health and safety						
Repairs						

The mix of measures installed in the 31 field test homes were different than those installed in houses located in the hot-climate region in 1989 when the last national evaluation of the Program was performed (Brown et al. 1993). Five measures that were performed more frequently in the study homes compared to the homes weatherization in 1989 are:

- Blower-door-guided infiltration work—performed in 97% of the study homes but in only 1.4% of the houses in 1989.
- Attic insulation—performed in 74% of the study homes but in only 43.0% of the houses in 1989.
- Wall insulation—performed in 39% of the study homes but in only 1.1% of the houses in 1989.
- Measures involving the space-heating system—replacement units installed in 16% of the study homes compared to any space-heating system work being performed in only 3.7% of the houses in 1989.
- Replacement air conditioners—installed in 68% of the study homes but in essentially none of the houses in 1989.

4.3 INSTALLATION COSTS

Table 4.3 shows the distribution of average costs for measures installed in 31 of the 35 study houses (17 standard procedures group houses and 14 demonstration group houses) as reported by the BWRs. The total costs for all measures installed average $5,053 per house. Average repair costs included heater repairs, plumbing, exterior siding, and mobile home roofs and floors. Although these costs imply that many repairs were performed, many other repairs were left undone. Only one site-built home had a replacement roof installed, despite the fact that two other site-built houses had roofs that were clearly old and in need of replacement but had not yet started leaking. In two site-built homes, ceilings were not insulated because of the presence of knob-and-tube wiring. Replacing this obsolete wiring would have allowed attic insulation, one of the most cost-effective weatherization measures, to be installed, but the additional cost of replacing the wiring made the ceiling insulation too costly.

Table 4.3. Average measure costs per home

Measure type	All houses (31 houses)
Cost effective by both NEAT/MHEA and EASY:	
Infiltration reduction	$746
Attic insulation	$618
Wall insulation	$289
Subtotal	*$1,653 (33% of total)*
Cost effective by EASY only:	
Window replacements	$215
Storm windows	$410
Door replacements	$475
Air conditioner replacements	$632
Subtotal	*$1,732 (34% of total)*
Health, safety, and repair:	
Heater replacements	$383
Health and safety measures	$394
Repairs	$891
Subtotal	*$1,668 (33% of total)*
Total, all measures	*$5,053*

The total cost of $5,053 was evenly distributed among three types of measures: those that both EASY and NEAT/MHEA determined would save energy and be cost effective; those that could save energy but were cost effective only by EASY's estimates but not NEAT/MHEA's estimates; and health, safety, and repair items that neither of the audits recommended based on energy savings and cost-effectiveness considerations.

4.4 THE WEATHERIZATION DECISION PROCESS

The purpose and scope of the Program as currently stated in the Code of Federal Regulations (CFR) 10CFR 440.1 is "to increase the energy efficiency of dwellings owned or occupied by low-income persons, reduce their total residential expenditures, and improve their health and safety" (Code of Federal Regulations 2005). As part of the weatherization decision process, states and local agencies often struggle with three things in implementing the Program as outlined: balancing expenditures among these three areas of Program emphasis, dealing with inherent conflicts between these areas, and the lack of tools to guide decisions regarding health and safety improvements.

The pattern of weatherization and repair measures selected in the study homes (see Table 4.2) and the distribution of costs provided in Table 4.3 provide insight into how TDHCA and its local agencies balanced these Program priorities. It is clear that making housing repairs and improvements, improving quality of life, and ensuring comfortable and safe indoor temperatures are important elements of Texas' overall program.

Shifting priorities to spend more of the available funds on cost-effective measures and less funds on health, safety, and repairs would clearly improve the Program's cost effectiveness (given that all cost-effective measures are already being installed in homes, such a shift would involve weatherizing more houses, but spending less per home). However, it is reasonable to ask if it makes sense to limit measures to those that achieve cost-effective energy savings when the other needs of the house and occupants are so great. Adding to the complexity of balancing expenditures among these Program priorities is that funding sources other than just Program funds are used, which may have their own rules and priorities. For example, in the study homes, funds provided by Entergy, the local utility, were available to install replacement air conditioners.

The Program's two goals of making cost-effective energy-efficiency improvements and improving health and safety can be in conflict. For example, broken air conditioners were replaced with new units in some of the study homes. Although such replacements improve the health of the occupants by improving the indoor temperatures of the home during the summer and possibly reducing mold and mildew problems, it is likely that use of the new air conditioners will result in an increase in energy use and expenditures rather than a decrease. Similarly, installing replacement air conditioners with increased cooling capacity and replacing space heaters that were not working or were unsafe to use, as was done in many study homes, is more likely to increase energy consumption than to reduce it. When little energy is being used because of inadequate or broken equipment, there is little opportunity to reduce energy use by installing additional energy-efficient equipment.

Energy audits like NEAT/MHEA and EASY provide recommendations on measures that should be installed that are based only on considerations of cost-effective energy savings. Judgments based on more than simple cost effectiveness are needed to guide the selection of health, safety, and repair measures, but no automated tools like energy audits are available to provide such guidance.

In the demonstration group, NEAT/MHEA did not recommend the installation of replacement windows and doors, or the installation of replacement air conditioners except in one house. However, EASY did. If audits, as their accuracy is improved, do not recommend measures that were previously thought to be cost effective, then less money will be spent on each house, more houses will be weatherized, and house and Program cost effectiveness should increase. Spending a planned amount of money each year would require auditing a larger number of houses. Audits take time and effort. Consequently, the costs of audit and other overhead items per weatherization measure installed will increase and make the weatherization provider appear to be less efficient. Such a change would require a change in the expectations for weatherization providers.

5. PRE-WEATHERIZATION ENERGY CONSUMPTIONS AND INDOOR TEMPERATURES

In this section, the energy consumptions measured in the study homes before weatherization are presented, along with examples of energy-use patterns and indoor temperatures observed in some of the homes. Results are presented for all the study homes combined, rather than by the two weatherization groups (demonstration group and standard procedures group), because the focus is on the homes and the behavior of the occupants before any weatherization activity took place.

5.1 PRE-WEATHERIZATION ENERGY CONSUMPTION

In 17 of the 18 demonstration homes audited by ORNL, the pre-weatherization heating and cooling energy consumptions estimated by NEAT and MHEA were compared to actual consumptions estimated by PRISM to put the pre-weatherization energy consumptions of the study homes into some context and to gain some insight into the accuracy of the NEAT and MHEA audits used to select measures in the demonstration group.[14] NEAT and MHEA calculate the pre-weatherization heating and cooling energy consumption of a home as part of their process of estimating energy savings for weatherization measures and developing weatherization recommendations. Over predicting pre-weatherization energy consumption likely leads to an over prediction of energy savings for weatherization measures, which then leads to recommendations for installation of more weatherization measures than is cost effective.

Figures 5.1 and 5.2 show the ratio of actual pre-weatherization energy use to consumptions estimated by NEAT and MHEA for each house for heating and cooling, respectively. A ratio of 1.0 means that the actual energy use was accurately predicted. A ratio less than 1.0 means that the actual energy use was less than the predicted energy use. The results show that, before weatherization, most houses used less heating and cooling energy than NEAT and MHEA predicted, and that the ratios varied considerably between houses. [15] For space heating, the ratios for 11 of the 17 houses were between 0.5 and 1.2, and averaged about 0.75. This is consistent with other studies of NEAT and MHEA, which found that they over predicted, on average, pre-weatherization space-heating energy consumption by between 10−35% (Ternes 2007).

NEAT’s and MHEA’s calculations are engineering based, and NEAT and MHEA use in their calculations the characteristics of the audited house. However, NEAT and MHEA, like most energy audits used to select weatherization, also generally assume that indoor temperatures are maintained at fixed levels throughout the winter and summer (for this study, these temperatures were assumed to be 70°F in the winter and 73°F in the summer) and that the heating and cooling equipment has sufficient capacity to maintain these temperatures (at least in the floor area that is considered to be conditioned[16]). In the next section (Sect. 5.2), the accuracy of these assumptions is explored.

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[14] Data were not available for on demonstration home, and comparable results were not available for houses that were audited with EASY because EASY did not report separate pre-weatherization energy consumption estimates.

[15] ORNL saw no evidence that the use of either wood stoves or kerosene heaters were a factor.

[16] In homes heated by space heaters or cooled by window air conditioners, which is common in houses in the hot-climate region, the entire floor area of the house may not be heated or cooled. NEAT and MHEA allow the auditor to enter the actual amount of floor area that is heated or cooled, which requires some estimation on the part of the auditor to factor in the number of space heaters and window air conditioners with room layouts.

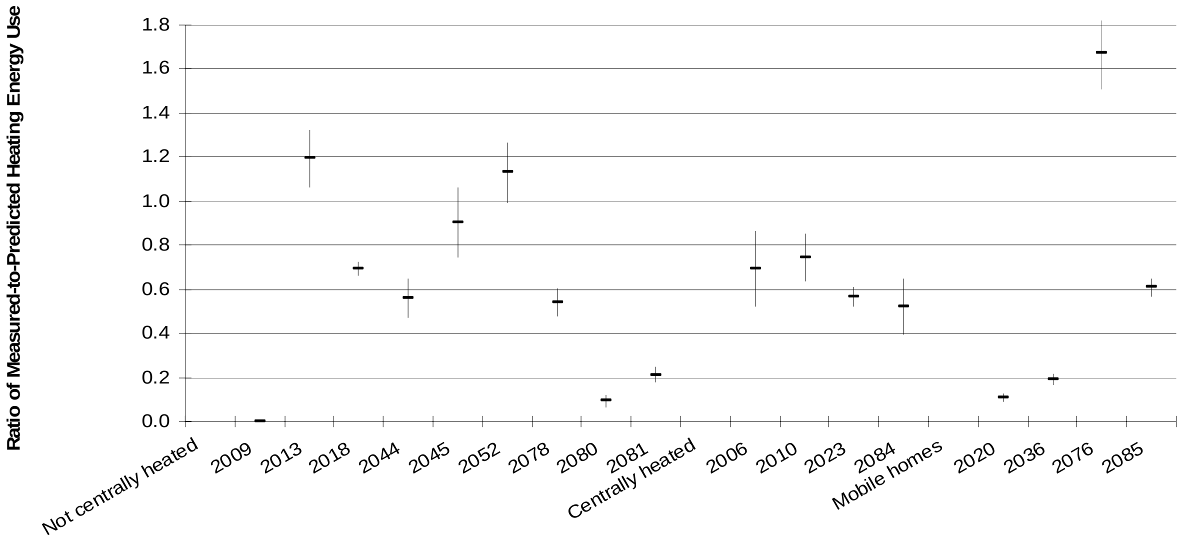

Figure 5.1. Ratio of measured to predicted heating energy use. Vertical bars represent the 95% confidence interval on the measured energy use.

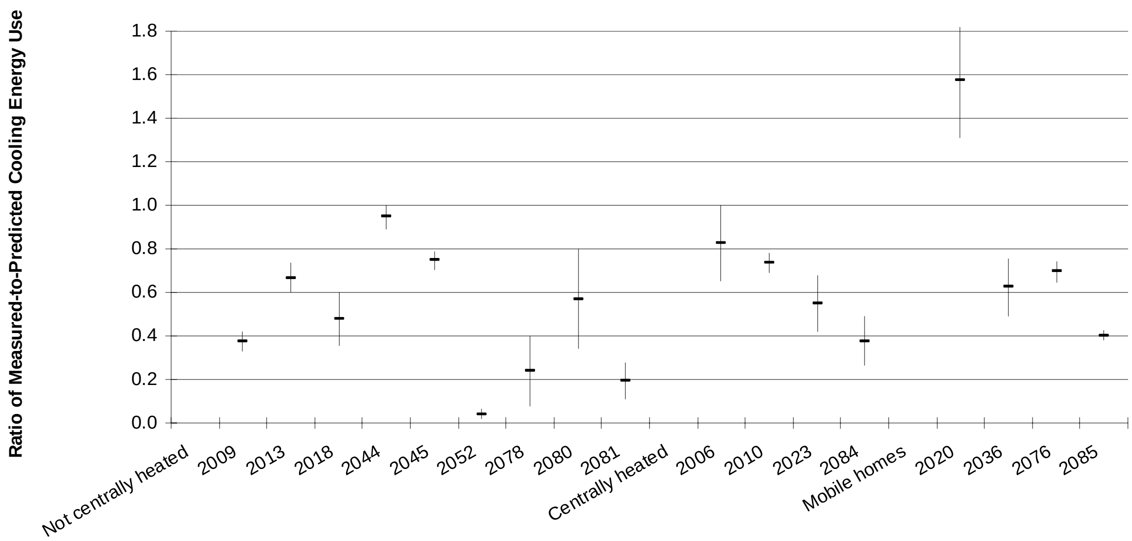

Figure 5.2. Ratio of measured to predicted cooling energy use. Vertical bars represent the 95% confidence interval on the measured energy use.

5.2 PRE-WEATHERIZATION ENERGY-USE PATTERNS

This section analyses household energy loads and indoor temperatures monitored in the study homes before weatherization to identify occupant behaviors and heating and cooling operational characteristics that can be impacting weatherization performance and audit predictions in hot climates. As discussed in Sect. 2.3, extracting electric consumptions for heating, air conditioning, and other appliances from the total house electrical consumption was difficult. Therefore, a case study approach was undertaken in the analysis in this section, where loads and associated indoor temperatures were extracted and analyzed for just some homes for selected time periods.

As discussed in Sect 2.3, one temperature probe was installed in each house where the occupants spent most of their waking hours, typically in a living or family room. One limitation of the indoor temperature data is that a single indoor temperature monitored in a house may not accurately reflect the temperatures of other parts of the house, especially in the houses that were not centrally heated and cooled. Outdoor temperature data needed for the analyses in this section were obtained from the National Weather Service for the Beaumont and Nacogdoches weather stations. These data should be reasonably representative of what was experienced by the houses served by the two agencies.

Several patterns of energy-related occupant behavior were observed from analysis of the pre-weatherization data. There is strong evidence that, at least part of the time during the pre-weatherization period, some houses were not heated during cold weather or were not air conditioned during hot weather. In some cases, energy-use patterns of other appliances suggested that the occupants were absent from these houses for extended periods.

Figure 5.3 shows daily heating electricity use (filled circles) and daily average indoor temperature (+ sign) plotted against daily average outdoor temperature for a house that was centrally heated with electricity. For each day, there is an indoor temperature (+ sign) with a corresponding heating electricity use (filled circle) unless no heating energy was detected for the day, in which case there is a temperature (+ sign) with no corresponding filled circle. The filled circles that are just above zero are probably water-heater energy use that NIALMS misidentified as space heating. Most of the time, the daily average interior temperature was between 68°F and 75°F. For those days when the indoor temperature was near 68°F and the outdoor temperature was less than 65°F, there was a corresponding heating energy use that increased as the outdoor temperature dropped, indicating that the furnace was turned on and the thermostat set to maintain a desired temperature. However, there were a large number of cold days (average outdoor temperature below 60°F) during which the average indoor temperature was considerably less than 65°F. In almost all cases where the outdoor temperature was less than 60°F and the indoor temperature was less than 65°F, there was no corresponding heating energy use for the day, indicating that the furnace was turned off and/or the thermostat set back such that the furnace did not turn on.

Figure 5.4 is a plot of appliance energy use and indoor temperature for a single house on December 21, 2001. The pattern is exactly what would be expected for an unoccupied house during the heating season with the furnace turned off. The furnace did not come on at any time during the 24 hours. The interior temperature ranged from about 56°F to 62°F, which is considerably lower than what would be expected in an occupied house, and fell through the night and rose in the late morning as the outdoor temperature increased. The electric water heater cycled on periodically with no extra cycles that would be indicative of someone using hot water. The refrigerator cycled on and off at approximately regular intervals. While it is not unusual for people to be away from home for a day, close examination of other data for the house shown in Fig. 5.4 revealed that this house was unoccupied for more than 50 days during the pre-weatherization winter. If this is typical behavior for this occupant, the potential heating energy savings of

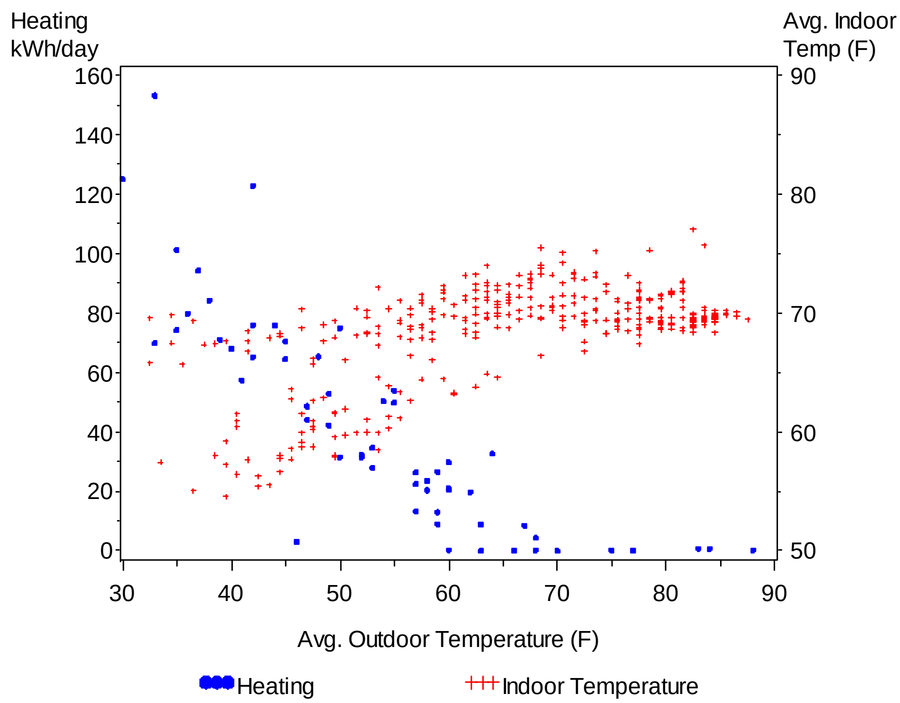

Figure 5.3. Example of a house that was heated intermittently during the winter. Daily heating electricity use and daily average indoor temperature by daily average outdoor temperature.

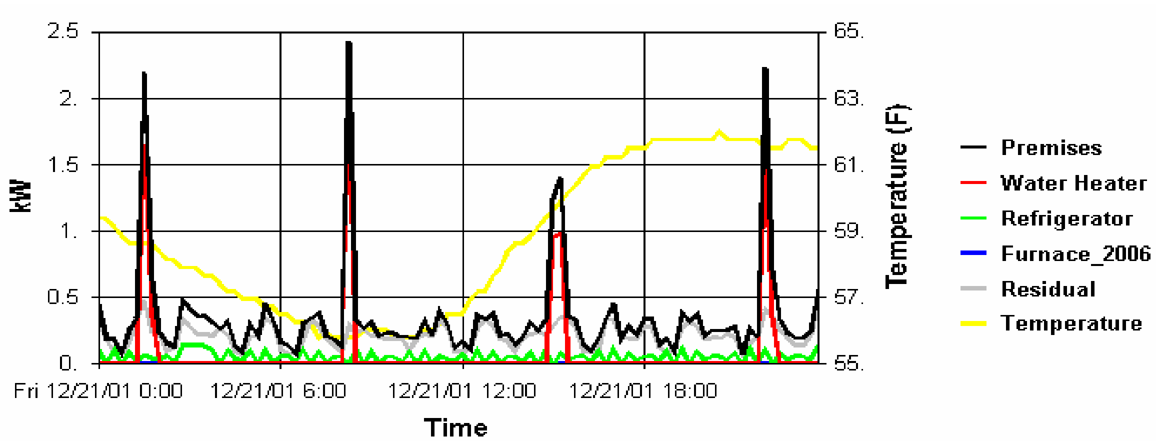

Figure 5.4. Example of appliance electricity loads and interior temperatures of a house during a period when the house was unoccupied.

the house would be about half what would be expected for a house that is occupied full time. Alternatively, if this was an unusual period of absence, resuming full-time occupancy of the house after weatherization would almost certainly lead to an increase in energy use despite any efficiency improvements achieved by weatherization. In the absence of knowledge of occupant absences, comparing pre- and post-weatherization energy consumption would lead to the conclusion that weatherization of this house increased, rather than decreased, energy consumption.

Figure 5.5 shows the interior temperature and air conditioning electricity use of a house that was largely unheated and only intermittently cooled. The interior temperature was usually about the same as or a little warmer than the outdoor temperature. When the average outdoor temperature was less than 65°F, the average indoor temperature ranged from being equal to the average outdoor temperature (indicating no heating) to sometimes being as much as 10°F warmer than the average outside temperature (indicating heating from internal loads, solar heating, or partial heating by the occupants). Even though the house had a gas furnace and the occupants reported that they occasionally using portable electric heaters, there was clearly no effort to keep the house at consistently comfortable temperatures during the winter.

During the cooling season when the average outdoor temperature was greater than 75°F, there were some days when the house (or at least the room with the temperature sensor) was cooled and other days when it was not (as evidenced by the high interior temperatures and the very low cooling energy consumptions).

In addition to the energy-related occupant behavior patterns described above, there were other equipment-related energy-use patterns that showed that, in some homes before weatherization, the air conditioning system could not keep the house at the desired temperature during the hottest part of the day. One notable feature of Fig. 5.5 is that the air conditioning electricity consumption often reached a plateau of about 20 kWh/day, about the amount of electricity that one window air conditioner would consume if it ran continuously for 24 hours. Apparently, when the house was cooled, the air conditioner often ran at capacity for the whole day. Furthermore, the indoor temperature was higher at higher outdoor temperatures when the air conditioner ran continuously.

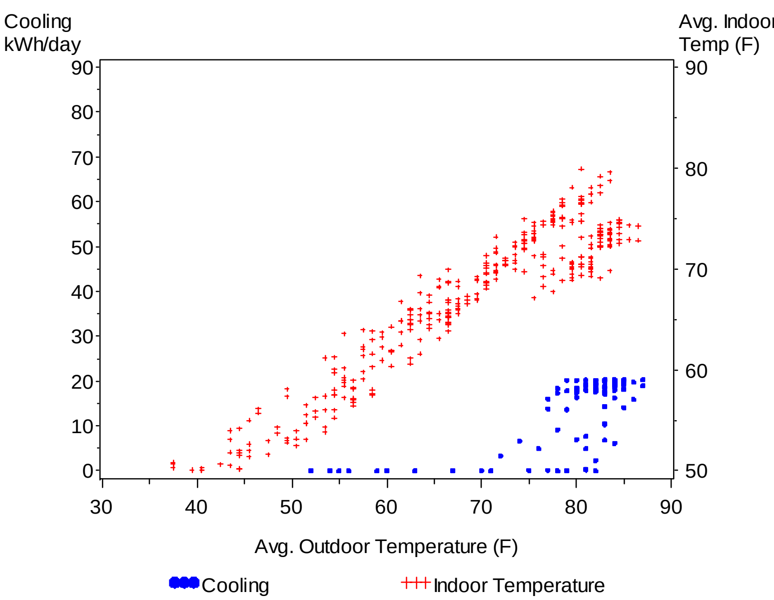

Figure 5.5. Example of a house that was largely unheated and only intermittently cooled. Daily air conditioner electricity use and daily average indoor temperature by daily average outdoor temperature.

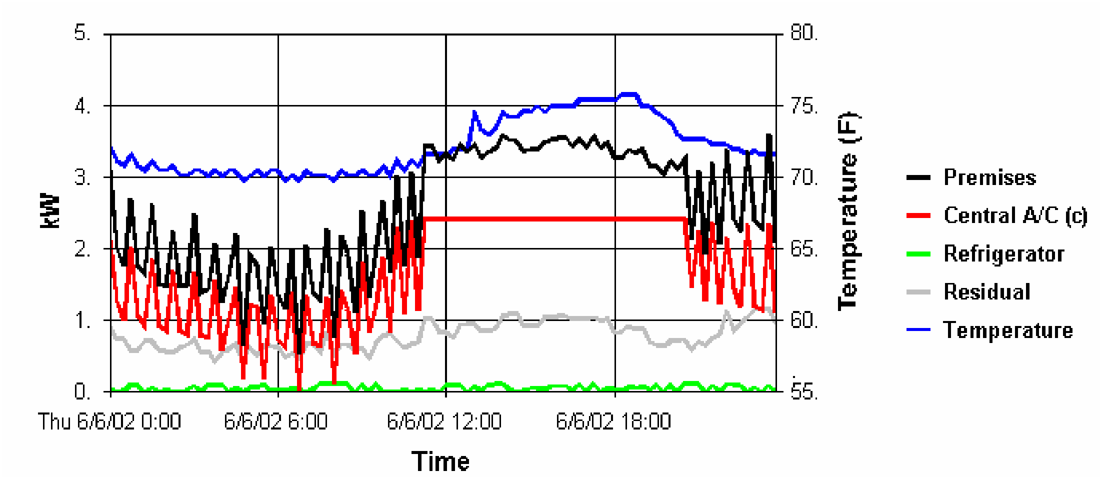

Figure 5.6. Example of a house with an air conditioner that cannot maintain the desired interior temperature during the hottest part of the day.

Figure 5.6 shows appliance energy use and indoor temperature for a single house on June 6, 2002. This house had a central air conditioner that could not maintain the interior temperature at the desired level, even while running at full capacity. Until about 11 a.m., the air conditioner cycled on and off to keep the house close to 70°F. From about 11 a.m. until about 8 p.m., the air conditioner ran continuously while the interior temperature drifted above 75°F and the 70°F that appeared to be the occupant's preferred indoor temperature.

Finally, the energy-use pattern of one house suggests how space heaters and window air conditioners are unable to condition the entire floor area of a home and how extreme temperature variations are created in the house as a result. Figure 5.7 shows a house that was heated by an unvented gas space heater in the living room, and cooled by one window air conditioner in each of the two bedrooms. During the heating season when the average outdoor temperature was below 65°F, the room with the temperature sensor was maintained between about 75°F and 83°F. It should be noted that this temperature range is substantially higher than the 68°F to 70°F assumed by most energy audit programs, although the room with the space heater may have been overheated to help warm the unheated bedrooms. Not surprisingly, this house used about 27% more natural gas for heating than NEAT predicted.

Figure 5.7 also shows that operation of the air conditioners in the bedrooms did not seem to affect the indoor temperature maintained in the main living area of the house. Indeed, the daily average indoor temperature in the main part of the house was sometimes higher than the outdoor temperature despite the air conditioner use in the bedrooms.

In summary, these examples present strong evidence that not all houses are maintained at the fixed temperatures often assumed in energy audits throughout the winter and summer. Explanations as to why energy consumptions and energy savings are less than expected include: (a) the heating and cooling equipment is not operated to maintain conditioned temperatures 24 hours a day throughout the winter and summer; (b) the heating and cooling equipment may be operated, but their capacity is insufficient to maintain desired temperatures; and (c) heating and cooling equipment may be operated, but they are not operated to condition as much floor area as might be assumed in an audit. On the other hand, there was evidence that the temperatures maintained in some homes were higher in winter and lower in summer than assumed, which would lead to higher energy consumptions and savings than expected.

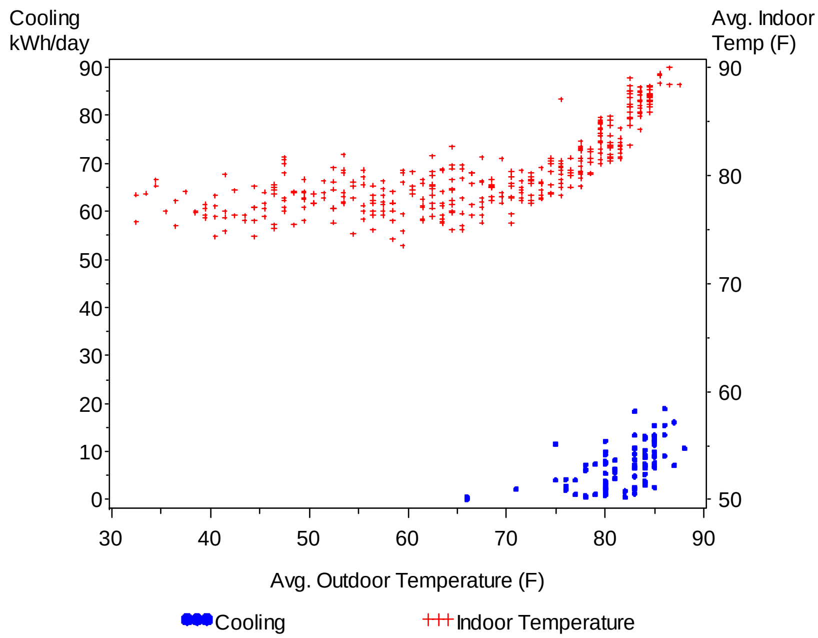

Figure 5.7. Example of a house with adequate heating but inadequate cooling. Daily cooling electricity use and daily average indoor temperature by daily average outdoor temperature.

5.3 AUDIT IMPLICATIONS

The over predictions of energy consumption observed in Sect. 5.1 and the occupant and equipment behaviors observed in Sect. 5.2 suggest that the accuracy of NEAT and MHEA (and audits in general) could be improved if the audits were programmed to account for the actual behaviors that occur in the homes. For example, house-specific indoor temperatures, daily operational patterns of the heating and cooling equipment, occupancy schedules during the day and year, etc. could be input directly.[17] Alternatively, energy-saving predictions could be adjusted based on a comparison of actual to predicted pre-weatherization energy consumption as the actual pre-weatherization consumption includes the effects of house-specific indoor temperatures, occupancy, etc.

NEAT and MHEA provide a simple, optional means for adjusting space-heating and space-cooling energy savings estimates based on how well their prediction of pre-weatherization space-heating and space-cooling energy use compares to actual energy use. Simplistically, for space heating, NEAT and MHEA use historical utility bills input by the auditor to calculate a ratio of actual pre-weatherization space-heating energy use based on billing data to predicted pre-weatherization space-heating energy use based on audit parameters and assumptions. They then multiply projected space-heating energy savings by this ratio, which leads to smaller predicted energy savings and recommendations for fewer weatherization measures if they were initially over predicting pre-weatherization energy consumption. A similar calculation is performed for space cooling.

[17] NEAT and MHEA already allow the auditor to enter the actual amount of floor area that is heated or cooled, an input that was used in this study.

Two issues arise as audits are made more accurate by accounting for house-specific occupant and equipment behaviors. First, one must consider whether the house is being weatherized because of how the current occupants operate it, or is the house being weatherized by how it might be occupied and operated over the long term (say 20 years). The long-term perspective has merit when the following are considered: the long lifetime of most weatherization measures (15 to 20 years), the fact that houses often change occupants within 5 years[18], and the restriction that houses cannot be re-weatherized by the Program until many years have passed. Although basing audit recommendations on current occupant and equipment behaviors could increase audit accuracy for the present occupants, it could result in less-than-optimum results for the long term when other people occupy the house.

Second, there is a fairness issue that must be addressed. Improving audit accuracy by accounting for house-specific occupant and equipment behaviors could lead to fewer measures being installed in houses where (a) the occupant practices energy conserving behaviors or lacks the means to heat or cool the house to more comfortable temperatures, and/or (b) the current heating and cooling equipment is inoperative and/or of insufficient capacity to heat and cool the entire home. Conversely, an occupant who overheats or overcools their house is likely to benefit from the recommendation and installation of more weatherization measures. From an energy conservation point of view, these are the desired results. From other perspectives, it may be seen as unfair because such a program may tend to reward those who (a) have the better heating and cooling equipment capable of conditioning their entire home than those with inoperative or non-existent equipment, and (b) those who are not careful about energy consumption than those who are.

Continuing the current practice of ignoring the actual house-specific occupant and equipment behaviors avoids the fairness issue, but may lead to the installation of measures that do not achieve cost-effective energy savings for the existing occupants. Although non-cost effective measures may have benefit to the occupant, the fact that they are not cost effective suggests that there may be other, more beneficial things the money could do for the occupant or the group of clients served by the Program.

[18] As discussed in Sect. 2.1, occupants of 11 of the 57 houses (~20%) originally in the field study moved out during the two-year test period. Also, DOE reports that about 30% of occupants plan on living in their current home five years or less (DOE, 1992).

6. WEATHERIZATION IMPACTS

In this section, the energy savings measured in the study homes are presented, along with the indoor temperature changes that occurred following weatherization. Results are presented for all the study homes combined, rather than by the two weatherization groups (demonstration group and standard procedures group), which would have allowed comparisons between the two different audit approaches, for two reasons:

- Larger-than-expected attrition occurred, such that the remaining number of homes in each of the standard procedures and demonstration groups was too small to determine differences between groups with any statistical confidence; and

- as described in Sect. 4.1, the weatherization measures installed in the two groups were about the same, negating any differences between groups.

During the study years (2001 through 2003), the weather that occurred was typical for the study locations. For the Beaumont area, annual heating degree days ranged from 1,335 to 1,440 at base 65°F during the study period compared to 1,447 heating degree days typical, and the annual cooling degree days ranged from 2,806 to 3,066 at base 65°F compared to 2,823 cooling degree days typical. Similarly, the Lufkin weather station reported between 1,913 and 2,039 annual heating degree days for the study period compared to 1,900 heating days typical, and between 2,520 and 2,694 annual cooling degree days compared to 2,480 cooling degree days typical.

6.1 ENERGY SAVINGS

Twenty-four homes[19] had sufficient energy consumption data that could be analyzed with PRISM to determine their energy savings from weatherization: 11 homes heated by natural gas and 13 homes heated by electricity. As shown in Table 6.1, the average annual natural gas savings in the 11 gas-heated study homes was 140 therms, and the average annual electricity savings was 1,100 kWh (although the confidence interval indicates that the electricity savings are not statistically different from zero at a 95% confidence level). Because these houses were heated by natural gas, the electricity savings should mainly reflect the effects of weatherization on space cooling. In the 13 electrically heated houses, the average annual electricity savings was 1,800 kWh (a value that is right at the edge of statistical significance), which reflects the effects of weatherization on both space heating and space cooling.

Table 6.1 Annual energy savings

House type and fuel	Annual energy savings	95% confidence interval
Gas-heated homes (11):		
Natural gas	140 therms	90 to 190 therms
Electricity	1,100 kWh	-870 to 3,100 kWh
Electrically heated homes (13):		
Electricity	1,800 kWh	0 to 3,600 kWh

[19] Of the 35 houses in the field study, 4 were unsuitable for this analysis because the heating system fuel changed from electricity to natural gas or vice-versa as part of the weatherization: 3 gas-heated homes were converted to electric heat, and 1 home that had been heated by portable electric space heaters after the gas wall furnace broke was converted back to gas heat by installing a new wall furnace. Seven other houses had insufficient pre- or post-weatherization energy data to allow analysis of energy savings.

These results are consistent with previous studies of houses in hot climates that showed significant gas savings, but cooling savings that were not statistically significant. Compared to the results from the 1989 national evaluation of the Program (Brown et al. 1993), the results show that improved savings have been achieved in the study homes as the savings achieved in the study homes are more consistent with the higher savings achieved previously in the moderate climate than the hot climate. From the 1989 evaluation, the gross[20] annual energy savings for homes heated by natural gas in the hot climate was 102 therms, but 137 therms for the moderate climate (electricity savings in gas-heated homes were not measured in the 1989 evaluation). Similarly, in electrically heated homes, the savings was 307 kWh in hot-climate homes and 939 kWh in moderate-climate homes.

Figures 6.1 to 6.3 display the energy savings measured in the individual houses. The diamonds indicate the best estimates of savings for the houses while the vertical bars indicate the 95% confidence interval for the estimates (i.e., the interval in which one is pretty confident that the actual savings lie). Figures 6.1 to 6.3 show that there is much house-to-house variation in energy savings. In the houses heated by natural gas, annual gas savings were all positive (although two were not statistically significant savings) and varied from about 25 to 250 therms. The range of annual electricity savings in the gas-heated homes was very great, from −2,000 to 9,000 kWh, with five of the houses experiencing reduced electricity usage after weatherization and five showing increased electricity usage after weatherization (i.e., negative electricity savings). In the electrically heated homes, annual electricity savings ranged from about -5,000 to 6,000 kWh, with most of the houses (10 of 13) experiencing reduced electricity consumption.

A substantial amount of money was invested in replacing air conditioners (see Sect. 4.2), with replacement air conditioners being installed in more than half of the study houses. Most of these were through-the-wall or window air conditioners, but several houses received replacement central air conditioners. To study the impact of air conditioner changes on space-cooling electricity savings, annual electricity savings for homes that received air conditioner changes were compared to homes that had no cooling system changes. These results are shown in Table 6.2. For gas-heated houses, the electricity savings should be primarily due to space-cooling. For electrically heated homes, the electricity savings includes both space-heating and space-cooling. There are only a few houses in each group (three to five houses in each), so the confidence intervals on the average savings are quite large which makes the average savings not very reliable.[21]

For the gas-heated homes, there appears to be a trend toward larger electricity savings in houses that had more investment in air conditioners, but no such trend is evident for the electrically heated homes. For both sets of homes, savings were higher in homes receiving air conditioners in which the capacity increased rather than staying the same, which is opposite of what one would expect. However, for the gas-heated houses, the only difference between groups that is statistically significant is the difference between the group that had an air conditioner capacity increase and the group that had no heating or cooling system changes. For the electrically heated homes, none of the differences between groups are statistically significant.

[20] Gross rather than net savings are being used for comparison because the field study did not use a control group with which to calculate net savings.

[21] With a small number of houses per group, a single house in a group with non-normal savings can skew results. For instance, failure of one air conditioner in the post-weatherization period can look like energy savings. As another example, having a second person move in or out can make a substantial change in energy consumption patterns.

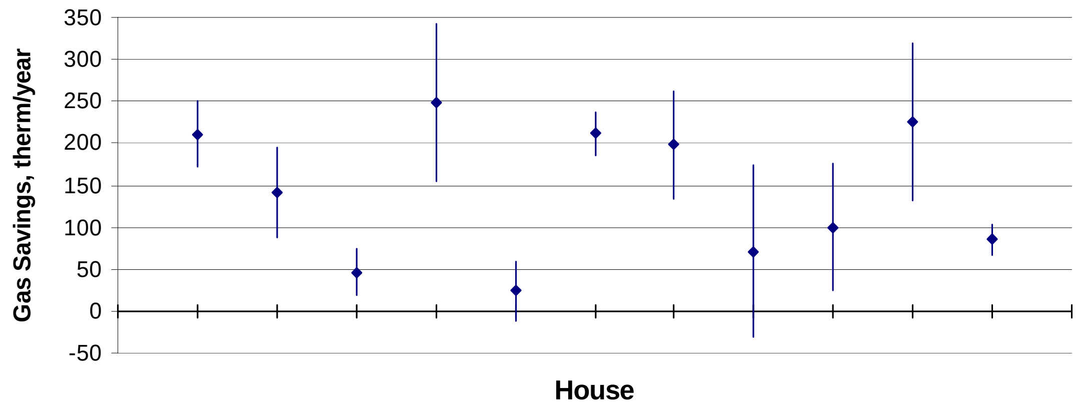

Figure 6.1 Gas savings of gas-heated study houses.

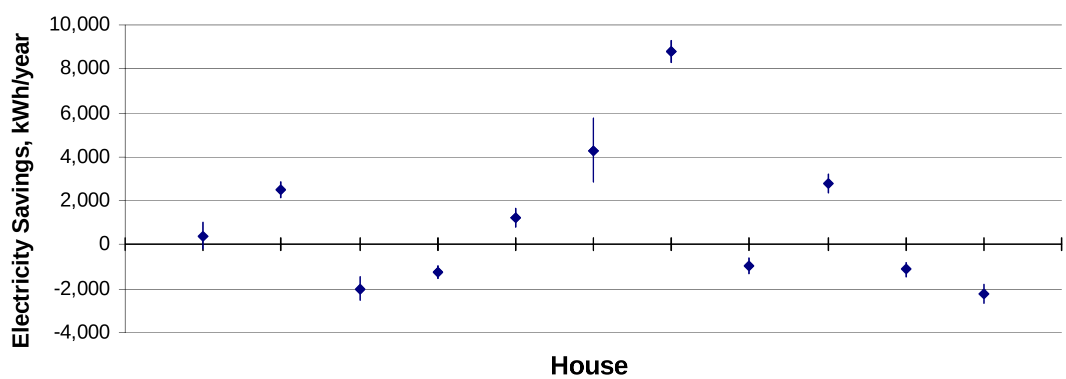

Figure 6.2 Electricity savings of gas-heated study houses.

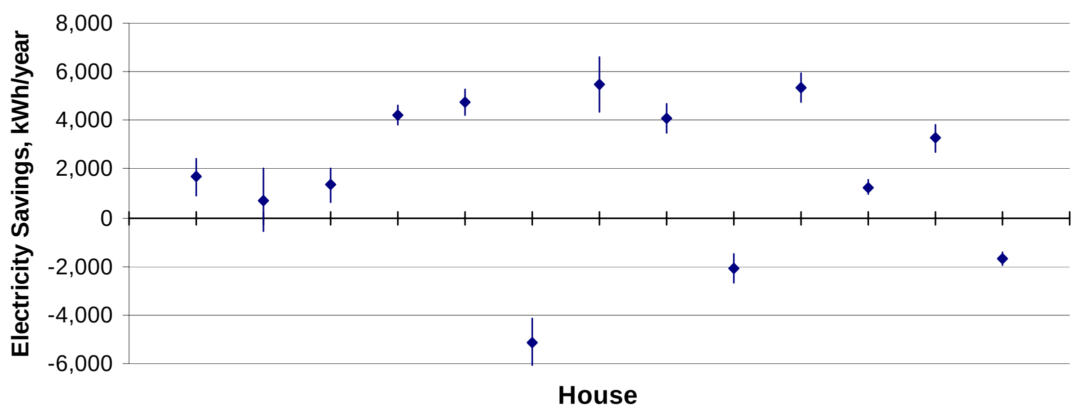

Figure 6.3 Electricity savings of electrically-heated study houses.

Table 6.2. Electricity savings due to weatherization and air conditioner replacements

	Air conditioner replaced, cooling capacity increased	Air conditioner replaced, no cooling capacity increase	No changes to cooling system
Gas-heated houses			
Number of houses	3	5	3
Average annual electricity savings, kWh	1,600 [a]	90 [a]	-1,200 [a]
Confidence interval, kWh [b]	−800 to 4,000	-1,600 to 1,700	-2,000 to -410
Electrically heated houses			
Number of houses	4	5	4
Average annual electricity savings, kWh	2,300 [a]	1,300 [a]	2,300 [a]
Confidence interval, kWh [b]	950 to 3,600	−2,100 to 4,800	−1,100 to 5,800

[a] Negative savings means an increase in energy consumption following weatherization. Because of the very small sample sizes and large confidence intervals, the authors do not consider the averages to be reliable estimates of the mean.
[b] The confidence interval used here is two standard errors about the average; approximately equal to a 95% confidence interval.
Note: Values have been rounded to two significant digits.

6.2. INDOOR TEMPERATURE CHANGES

As noted in Sect. 4.2, a substantial amount of money is invested in replacing air conditioners and, to a lesser extent, heating equipment. As previously discussed in Sect. 5.1, pre-weatherization temperature data indicated that some houses lacked sufficient cooling capacity to keep indoor temperatures at comfortable levels, and that some occupants heat and/or cool their homes (or at least the room with the temperature sensor) intermittently or not at all. This section presents an analysis of how indoor temperatures (and hence comfort) changed in response to weatherization and specifically to changes in air conditioning and heating equipment.

Four indoor temperature metrics were developed to perform this analysis. Two metrics addressed the average indoor temperature during the summer and winter when air conditioner and space-heating would normally be required. Two other metrics dealt with how frequently the indoor temperature was uncomfortably warm or uncomfortably cold[22] during the summer and winter, respectively. These metrics were:

- **Average warm-weather indoor temperature**—this is the average daily indoor temperature for a house for all days during the summer (about a 5- to 6-month summer season) when the average daily outdoor temperature was above 75°F.
- **Average cool-weather indoor temperature**—this is the average daily indoor temperature for a house for all days during the winter when the average daily outdoor temperature was below 60°F.

[22] The comfort range was taken to be 60−75°F. Indoor temperatures below 60°F were assumed to be uncomfortably cold, and indoor temperatures above 75°F were assumed to be uncomfortably warm. While choosing a different comfort zone would lead to different values of the metrics, the authors think other reasonable choices of the comfort zone would yield similar results.

- **Fraction of warm days with uncomfortably warm indoor temperatures**—this is the fraction of the days during the summer when the average outdoor temperature exceeded 75°F that the daily average indoor temperature also exceeded 75°F.
- **Fraction of cool days with uncomfortably cool indoor temperatures**—this is the fraction of the days during the winter when the average outdoor temperature was less than 60°F that the daily average indoor temperature was also less than 60°F.

Table 6.3 displays the results of the analysis of how weatherization and cooling system replacements affected summer indoor temperatures for 26 of the 35 houses that had sufficient indoor temperature data for analysis. Appropriate summer-related metrics are presented for three groups of houses: those in which a new air conditioner was installed that resulted in an increase in cooling capacity for the house (either a new unit was installed that had a higher capacity than the unit it replaced, a new unit was installed while leaving all existing units in place, or a broken air conditioner was replaced); those that had operating cooling equipment replaced with new units of the same capacity; and the remaining houses in which air conditioners were not replaced as part of the weatherization work performed.

The average warm-weather indoor temperature was about the same in all three groups of homes before weatherization (between 75°F and 76°F) and not statistically different from one another. All three groups showed improved indoor comfort during warm weather following weatherization (about 1°F to 2°F cooler), with the greater improvements occurring in the two groups of homes that received new air conditioners. The changes in indoor temperature are not statistically significant at about the 95% confidence level, except for those that occurred in the group of houses that received new air conditioners that resulted in an increased cooling capacity. Combining all three groups in Table 6.3 gives an average warm-weather indoor-temperature change of −1.8 °F, with a 95% confidence interval of −2.7 to −0.9 °F, which indicates that, overall, weatherization increased average warm-weather comfort levels.

As indicated by the differences between the average and median temperature changes, the magnitudes of the average changes were influenced by a few houses that had large decreases in indoor temperature. Large reductions in indoor temperature occurred in three of the capacity-increase group houses (-6.9°F, -4.7°F, and -4.4°F) and two of the replacement-without-capacity-increase group houses (-6.9°F and -5.3°F). The largest reduction in the group without any cooling system changes was -4.2°F. Evidently, weatherization was associated with substantial comfort improvements in some houses, although it is not clear that those improvements were attributable to cooling system changes.

The average fraction of warm days with uncomfortably warm indoor temperatures decreased after weatherization in each group such that the post-weatherization fractions were about the same in all three groups. The group that received a cooling capacity increase had a higher pre-weatherization fraction of days with uncomfortably warm indoor temperatures than the other two groups (32% compared to 16% and 18%). Although this suggests that, on average, air conditioning capacity increases were applied more frequently where they were needed most, this may not be the case when looking at houses individually. Four of the nine houses that received a cooling capacity increase had a pre-weatherization fraction of uncomfortably warm days of just 1% or less (i.e., they already maintained comfortable indoor temperatures throughout the summer). If air conditioner capacity increases are intended to improve comfort, it is apparent that they are applied to houses that already have comfortable summer temperatures about as often as to houses that are poorly cooled.

Table 6.3. Summer indoor temperature effects from weatherization

	Air conditioner replaced, cooling capacity increased[a]	**Air conditioner replaced, no cooling capacity increase**[b]	**No changes to cooling system**[c]
Number of houses[d]	9	10	7
Pre-weatherization average warm-weather indoor temperature	75.8°F	75.0°F	75.3°F
Average temperature change	−2.4°F	−1.7°F	−1.1°F
Confidence interval[e]	−4.1 to −0.7°F	−3.5 to +0.1°F	−2.3 to +0.1°F
Median temperature change	−1.6°F	−1.3°F	−0.9°F
Pre/Post weatherization fraction of warm days with uncomfortably warm indoor temperatures	32%/10%	18%/10%	16%/9%

[a] Houses that had an increase in cooling capacity due to replacement of a broken unit, addition of a new unit that did not replace an operating unit, or replacement of an operating unit with a unit of higher cooling capacity.
[b] Houses that had an operating air conditioner replaced with a new unit of equal cooling capacity.
[c] Houses that had no cooling system changes.
[d] The number of houses with the specified air conditioner treatments that also had sufficient pre- and post-weatherization indoor temperature data for analysis.
[e] The confidence interval is two standard errors about the average; approximately equal to a 95% confidence interval.

Table 6.4 displays the cool-weather results organized by type of heating system changes for 21 of the 35 study houses that had sufficient indoor temperature data for analysis. The average cool-weather indoor temperature before weatherization was lower in the group that did not receive any heating system work than the other groups, but the difference was not statistically significant. All three groups showed improvement in indoor temperatures. The average increases in cool-weather indoor temperature ranged from 0.4 to 1.9°F, but the confidence intervals show that the increases are not statistically significant at the 95% confidence level except for the group in which the heating capacity increased. Combining the three groups gives an average indoor temperature increase of 0.9°F with a 95% confidence interval of 0.1 to 1.7°F.

The group that did not receive any heating system work had the highest fraction of cool days with uncomfortably cool indoor temperatures both before and after weatherization. Although improvement was seen in this group following weatherization, little change occurred in the other two groups.

The averages discussed above obscure variability within groups. If one of the objectives is to improve occupant comfort by increasing heating system capacity, it is not clear that the heating system changes are being applied to the appropriate houses. Among the three houses that had heating capacity increases, the house with the lowest pre-weatherization average cool-weather indoor temperature had an average temperature of 64.5°F. Among the seven houses that received no heating system changes, two had average cool-weather indoor temperatures below 60°F. If increasing heating capacity is intended to improve comfort for low-income homes, auditors appear to be missing opportunities to help those who may need the most help.

Table 6.4. Winter indoor temperature effects from weatherization

	Heater replaced, heating capacity increased [a]	**Heater replaced, no heating capacity increase** [b]	**No changes to heating system** [c]
Number of houses [d]	3	11	7
Pre-weatherization average cool-weather indoor temperature	67.7°F [e]	68.0°F [e]	64.0°F [e]
Average temperature change	+1.9°F	+0.4°F	+1.3°F
Confidence interval [f]	+0.7 to +2.6°F	−0.9 to +1.7°F	0 to +2.6°F
Median temperature change	+1.5°F	+0.4°F	+1.8°F
Pre/Post weatherization fraction of cool days with uncomfortably cool indoor temperatures	8%/10%	7%/5%	26%/18%

[a] Houses that had an increase in heating capacity due to replacement of a broken unit, addition of a new unit that did not replace an operating unit, or replacement of an operating unit with a unit of higher heating capacity.
[b] Houses that had an operating heater replaced with a new unit of equal heating capacity.
[c] Houses that had no heating system changes.
[d] The number of houses with the specified air conditioner treatments that also had sufficient pre- and post-weatherization indoor temperature data for analysis.
[e] The differences in average pre-weatherization temperatures between groups are not statistically significant.
[f] The confidence interval is two standard errors about the average; approximately equal to a 95% confidence interval.

7. CONCLUSIONS AND RECOMMENDATIONS

The results from this study provide insight into the performance of the Weatherization Assistance Program in hot climates. They also raise questions about Program design and implementation. Conclusions and recommendations drawn from the study are discussed below.

7.1 ENERGY EFFICIENCY MEASURES AND SAVINGS

All of the homes ORNL visited in the study were insufficiently insulated and in need of general air sealing. Improved Program designs and the use of energy audits such as EASY and NEAT/MHEA resulted in better weatherization measures being installed in the study homes compared to those installed in hot climates in 1989, as evidenced by the improved energy savings achieved in the study homes (see below). The primary improvements were the use of blower doors to guide the infiltration work, more frequent installation of attic insulation, and installation of wall insulation. Replacements of space-heating and air conditioning equipment occurred more frequently in the study homes than in 1989, although the impact of these on energy savings could not be discerned from this study.

Qualitatively, the energy savings results were similar to previous studies in warm climates; namely, that savings in the primary space-heating fuel were statistically greater than zero, but electricity savings associated with space cooling were not statistically significant. Quantitatively, the space-heating energy savings achieved in the study homes heated by natural gas were higher than those measured in 1989 for homes in the hot climate and about equal to those measured in the moderate climate. The same is true for the electricity savings measured in the all-electric homes. Clearly, improved space-heating savings performance has been achieved since 1989.

Several occupant and equipment-related behaviors were observed from the data collected under this study that help explain why statistically significant electricity savings associated with space cooling could not be measured in the weatherized homes and why air conditioning energy consumption increased after weatherization in some houses. These are discussed in Sect. 7.3.

The study found that weatherization led to more comfortable indoor temperatures. On average, indoor temperatures were modestly, but significantly, more comfortable in the study homes after weatherization than before (about 2°F in summer and about 1°F in winter). In addition, the number of days in which the indoor temperature was uncomfortably warm during the summer or uncomfortably cool during the winter was less after weatherization than before. The impact of air-conditioning or space-heating equipment replacements on these indoor temperatures could not be discerned from this study.

7.2 WEATHERIZATION DECISION PROCESS

It is clear that many of the study houses were in poor physical condition and had been poorly maintained. As a result, they were often in need of significant health and safety measures and substantial repairs. This represents a key policy dilemma that Texas and other hot-climate states must struggle with. Namely, how to balance expenditures between installing cost-effective weatherization measures and performing health, safety, and repair items. The expenditures in the study homes exemplify how Texas balanced expenditures between these competing needs. On average, $1,668 was spent per house directly on health, safety, and repair items (about 33% of the $5,053 spent on the houses total) compared to $1,653 spent on infiltration and attic and wall insulation. In addition, $1,732 was spent on window and door treatments and air-conditioner replacements.

This study also highlights a second key policy dilemma for hot-climate states. Namely, that health, safety, and repair items can adversely affect energy savings, which further complicates the decision process that states and agencies must undertake. Although the installation of window and door weatherization treatments will almost always save energy (even if justified as a needed repair rather than based on cost effectiveness), the same is not true of replacement air conditioners and heating systems. New air conditioners or heating systems will likely save energy if the capacity of the new unit is the same as the capacity of the unit it is replacing, but new equipment that contributes to an increase in capacity (because the existing unit was inoperative or of a lower capacity than the new unit) may lead to increased air conditioning or space-heating energy consumption.

New air-conditioning or space-heating equipment that increases the cooling or heating capacity of the house, respectively, is not always installed in the houses where it is most needed. Of the nine houses that received cooling capacity increases, 4 already had comfortable pre-weatherization indoor temperatures (at least in the room in which the indoor temperature was being monitored). All three of the houses that received a heating system capacity increase had an average indoor temperature greater than 64.5°F, but two of the seven houses that did not receive any heating system work (and hence no capacity increase) had average pre-weatherization cool-weather temperatures below 60°F.

7.3 ENERGY AUDITS

NEAT/MHEA and EASY disagree on which weatherization measures are cost effective. The recommendations of both audits are similar concerning infiltration reduction, attic insulation, and wall insulation. However, EASY identified many homes in which window and door measures (i.e., replacements and other treatments) and air conditioner replacements were cost effective while NEAT/MHEA did not.

NEAT's and MHEA's pre-weatherization space-heating and air-conditioning energy consumption estimates were usually significantly greater than measured values. Over predictions of pre-weatherization energy consumption can lead to over predictions of energy savings for measures and recommendation of measures that are not cost effective. The amount that the audits over predict pre-weatherization energy use varied considerably between houses, indicating that no single adjustment applied to all houses would likely give improved results.

Several occupant and equipment behaviors observed in the field test homes help explain why audits may over predict energy consumptions and savings and why air-conditioning electricity savings are difficult to measure. To a lesser extent, these behaviors may also begin to explain why weatherization savings in hot climates are less than in other climates. These behaviors include:

- A house may not be occupied and conditioned the whole winter and/or summer. In the field study, several houses appeared to be unoccupied for extended or multiple short periods during which there was a lack of any space-heating or air-conditioning energy use. Consequently, both the frequency of absences and the amount of the energy use reduction during absences led to lower than expected energy consumption before and/or after weatherization in some Program homes.

- The occupants may choose not to run their heating or cooling equipment on certain days, especially under mild conditions.

- A house may not have sufficient heating and/or cooling capacity to maintain a comfortable temperature, especially before weatherization. In this study, there were several houses in which the capacity of the space conditioning equipment was clearly insufficient to keep the entire house at comfortable temperatures during the warmest or coolest weather before weatherization. For such houses, audits will overestimate energy use and, consequently, energy savings potential.

- The entire home may not be heated and/or cooled. In this study, there was strong evidence that only certain rooms were being heated and/or cooled in some homes that used space heaters or window air conditioners.

- Heating and cooling equipment, especially window air conditioners, may be turned on and off during the day, likely in response to when occupants are home during the day, a desire to air condition their bedrooms at night, etc.

- Installed heating and/or cooling equipment may not be operational during the entire winter and/or summer, especially before weatherization. In this study, many broken heating and cooling units were replaced during weatherization.

- The same temperature may not be maintained in all houses (70°F in the winter and 73°F in the summer were assumed in the NEAT audits performed for this study). The temperature data collected from this study shows that some occupants kept their homes colder in the winter and warmer in the summer than what is typically assumed to be comfortable and used in audits, which reduces their energy consumption and savings potential.

- The same temperature may not be maintained in a house before and after weatherization. On average, the study homes maintained more comfortable indoor temperatures after weatherization than before.

- In some houses, new air conditioners installed during weatherization replaced broken or inoperative units, or were larger than the existing units, such that the total cooling capacity of the house increased.

To improve audit accuracy (as typically measured by comparing audit predictions to first-year savings for the house occupied by the same occupants before and after weatherization), the specific occupant and equipment behaviors before weatherization would need to be entered into and used by the audit, and/or audit predictions would need to be adjusted to the actual pre-weatherization energy use of the house to account for the home's unique occupant and equipment behaviors. However, in doing so, the consequences must be acknowledged; namely, that (a) the houses occupied by the poorest people may have the least energy savings potential, (b) less investment may be made in homes where the occupants practice energy conservation or cannot afford to own or operate heating and cooling equipment that would keep their houses more comfortable, and (c) weatherization based on current occupant behavior may be less than optimal in the long run, when other people occupy the home.

7.4 RECOMMENDATIONS

States in hot climates should be encouraged to select from an expanded list of measures using advanced audits or other techniques as exemplified in this field study. These programs should be evaluated to ensure that improved performance is achieved and to identify further means of improvement. Comfort improvements should be assessed as part of these evaluations.

Given that air-conditioner measures are a growing element of weatherization programs in hot climates, further studies examining the benefits obtained from these measures are warranted. These studies should address energy savings, comfort improvements, and the impact of capacity increases on energy savings and comfort.

Given the magnitude of the investments being made in health and safety measures and repairs in this study, guidelines should be developed for the hot-climate states on how to balance the objectives of saving energy, improving health and safety, and addressing repair issues. Guidelines should also be developed on how to select repair items that address issues such as the quantity of repairs needed per home, the costs associated with these repairs, when it is appropriate to increase building heating or cooling capacity, the energy ramifications of the repairs (both energy savings and increased energy consumption), the comfort improvements from repairs, and the balance between doing more repairs on fewer homes versus being able to weatherize more homes. Weatherization providers have the benefit of energy audits and other diagnostic tools to guide their decisions on which measures are cost effective, but they have only their judgment to guide decisions on repairs and comfort issues.

Studies should be performed and guidance should be developed on whether Program objectives are best met by weatherizing houses based on actual or typical energy use, and current or long-term occupant behavior.

Finally, weatherization measures should be identified and tested that can improve the livability and comfort of hot-climate houses that have very low energy use and/or are not heated or cooled to normal, comfortable temperatures without increasing their energy consumption. For example, even a house that is not air conditioned could be made more comfortable if window shading were used to minimize solar heat gain in the summer. As another example, enhanced passive attic ventilation could reduce heat gain from the ceiling and improve comfort in a poorly cooled house.

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APPENDIX A. COMPARISON OF STUDY HOUSES TO RECS

To understand how the findings of this study fit into a larger context, this appendix describes comparisons of study house energy-use patterns with the energy use of comparable homes from the Residential Energy Consumption Survey (RECS). By comparing the study houses with RECS low-income houses from the same climate zone, it will be determined whether the usage patterns seen in the study houses can be expected to be representative of other low-income homes in the hot-climate region.

RECS, a periodic survey of the energy-use patterns of American households, collects data on a national sample of over 5,000 households. It uses a complicated sample design called "multistage area probability sampling" and is intended to represent the total population of more than 101 million U.S. households.[23] At the time of this study, the latest data available were from the 1997 RECS (DOE 1997).[24]

To make relevant comparisons with the study houses, information was extracted from the 1997 RECS Public Use Files on low-income homes located in Climate Zone 5, which includes parts of the United States that typically have less than 4,000 annual heating degree days and more than 2,000 annual cooling degree days. It covers most of Texas, all of Louisiana and Florida, and the southern parts of Mississippi, Alabama, Georgia, and South Carolina. The field study was conducted in cities with between 1,300 and 1,900 annual heating degree days and 2,500 and 2,900 annual cooling degree days. Closer examination of the RECS data revealed that some Climate Zone 5 houses were in regions with much higher cooling loads and smaller heating loads than experienced by the study houses. To refine the comparison, RECS entries were eliminated where the number of heating degree days was less than 1,000 or the number of cooling degree days was more than 3,500. Thus, the comparison described here involves RECS houses in climates with between 2,000 and 3,500 cooling degree days and between 1,000 and 4,000 heating degree days.

Because the best data on study houses were for the all-electric houses, only those RECS houses with electric heat that did not use either natural gas or liquefied petroleum gas as a supplementary heating source were selected. Finally, because RECS data showed that, on average, mobile homes use substantially more energy per square foot of living space than single-family detached houses, separate comparisons were made for mobile homes and for single-family detached houses. Therefore, the relevant groups of RECS mobile homes were compared with mobile homes from the field study, and RECS single-family houses were compared with single-family houses from the field study. In these comparisons, only electrically heated study homes that had a full year of pre-weatherization monitoring data were used.

A.1 SINGLE-FAMILY DETACHED HOUSES

Figure A.1 displays a comparison of total electricity use in 8 all-electric study single-family houses with a full year of monitoring data to those of 17 all-electric, low-income RECS houses in similar climates. The length of the columns represents the total annual electricity consumed for all end uses by each house. The average of the study houses is 15,300 kWh/year and the average of the RECS houses is 20,600 kWh/year; however, it is not clear that the difference is significant given the high variability and the small sample sizes. For the study houses, annual electricity use varies by a factor of about five, from just over 5,000 kWh to over 25,000 kWh. The RECS houses use between 8,000 kWh/year and 47,000 kWh/year. On the basis of total electricity use, the study houses appear quite similar to the comparable RECS houses. If anything, they use less total electricity than the RECS sample houses.

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[23] See the appendices of DOE/EIA-0632 (97).

[24] Data on low-income houses for this comparison were extracted from the 1997 RECS Public Use Files found at www.eia.doe.gov/emev/recs/public/html.

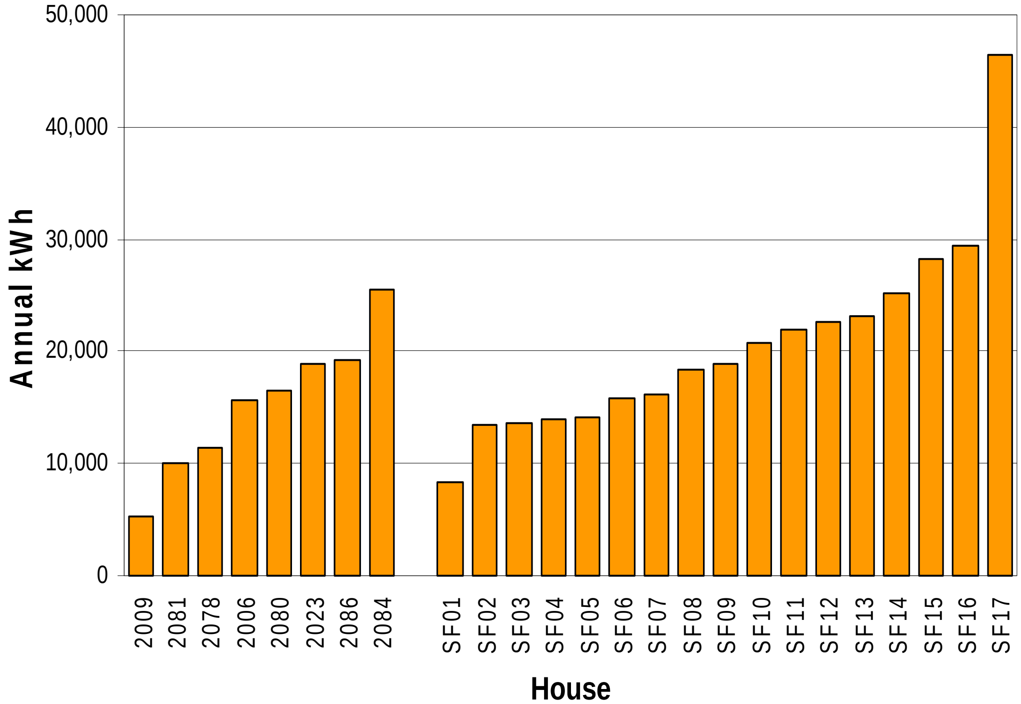

Figure A.1. Annual electricity use of all-electric study and RECS single-family detached houses. Study houses are labeled 20##. RECS houses are labeled SF##.

The study houses range in size from 987 to 1,614 ft^2 in floor area. The RECS houses range in size from 656 to 2,313 ft^2 in area. Larger houses normally use more energy, so Fig. A.2 presents total electricity per square foot of conditioned space. The variation between high and low usage is reduced slightly in the RECS houses when adjusted for floor area as compared to Fig. A.1, but the variation is reduced very little in the study houses.

House size is not, of course, the only factor affecting energy use. Heating and cooling energy use is strongly affected by outdoor temperature. A convenient way to represent the effects of climate on space heating and cooling energy use is with the parameters of heating degree days and cooling degree days. For example, by using heating degree days, heating-energy-use intensity values can be calculated by dividing annual heating energy use by heating degree days and floor area. Space heating and cooling are major energy uses so adjusting for heating and cooling degree days should reduce variability across houses. Figures A.3 and A.4 display heating and cooling energy intensities in watt-hours (Wh) per square foot per degree day (Wh/ft^2/degree day) for both the RECS and the study houses that heat with electricity. Again, the variation across houses is large, but the study houses follow about the same pattern of variation as the RECS houses.

The allocation of electricity use between different uses for the study houses is based on SPEED/NIALMS monitoring. The RECS estimates of appliance energy usage are based on detailed surveys and a non-linear regression technique, rather than the metering of individual appliances. Because each approach is subject to significant potential errors, heating and cooling energy use estimates should be understood to be less reliable than the total energy use.

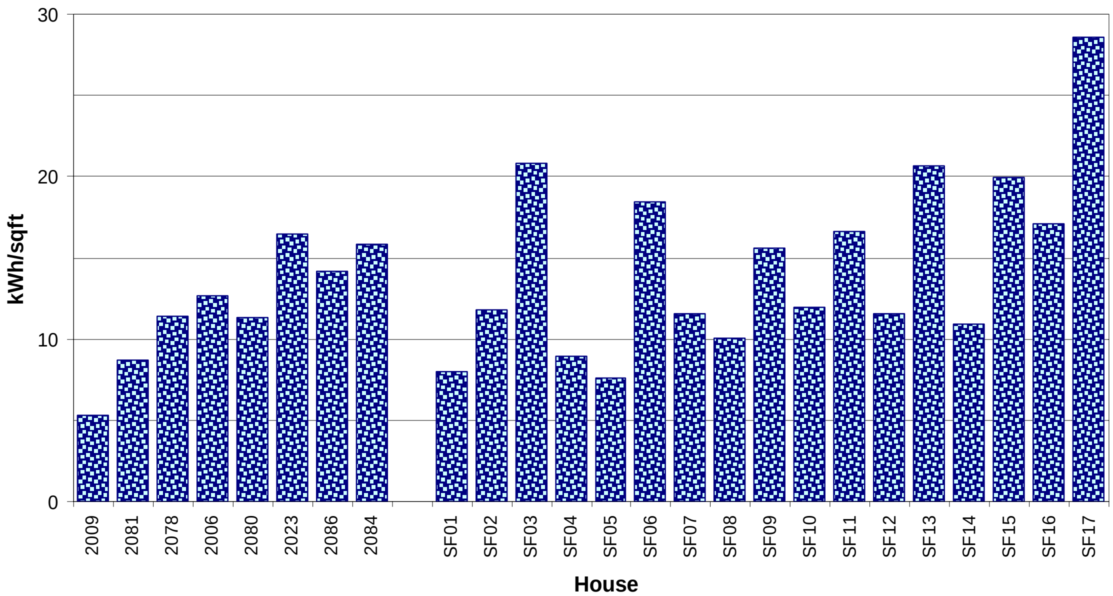

Figure A.2. Household energy intensity of all-electric study and RECS single-family detached houses. Study houses are labeled 20##. RECS houses are labeled SF##.

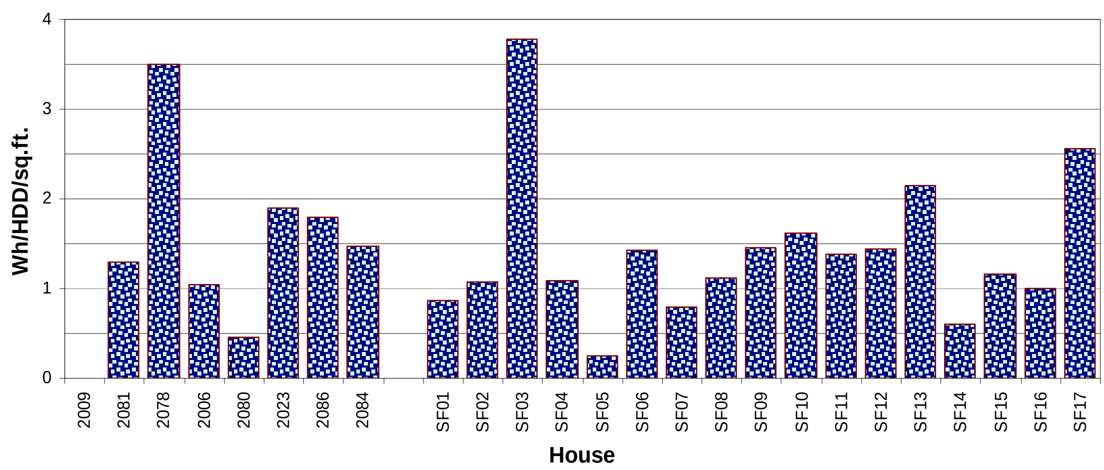

Figure A.3. Heating intensity of all-electric study and RECS single-family detached houses. Study houses are labeled 20##. RECS houses are labeled SF##.

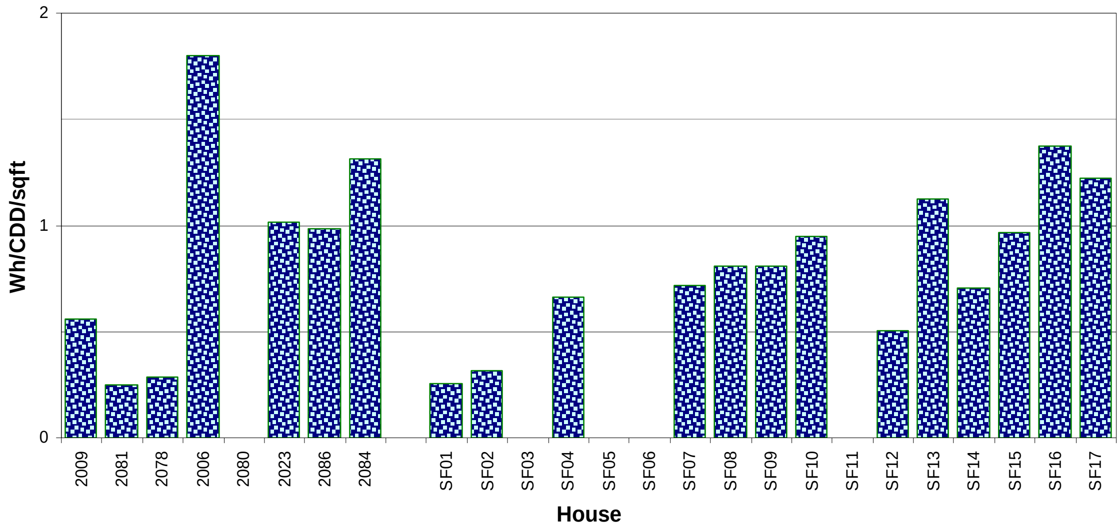

Figure A.4. Cooling intensity of all-electric study and RECS single-family detached houses. Study houses are labeled 20##. RECS houses are labeled SF##. Zero intensities result where no cooling energy use was reported.

A.2 MOBILE HOMES

Figure A.5 displays a comparison of the electricity use of the three all-electric study mobile homes with a full year of monitoring data to the energy-use patterns of the seven all-electric, low-income RECS mobile homes located in similar climates. The overall length of the columns represents the total annual electricity consumed for all end uses by each house. The three study mobile homes display electricity use similar to the RECS mobile homes, but with more variability.

The RECS mobile homes range in size from 741 ft^2 to 2,295 ft^2. All three study mobile homes discussed in this section have 1,064 ft^2 of conditioned space. Because space conditioning energy use usually rises as dwelling size increases, Fig. A.6 displays energy use adjusted for floor area and shows some reshuffling of the RECS mobile homes. However, the study mobile homes show no change in relative magnitudes.

Figure A.7 displays the space heating energy use intensities of the three study and the seven RECS mobile homes. Most of the RECS houses have intensities that lie between 0.8 and 1.2 Wh/HDD/ft^2. MH2 is an outlier among the RECS mobile homes with an intensity of more than 2.5 Wh/HDD/ft^2. The three study mobile homes continue to take up positions as highest (2057), lowest (2077) and right in the middle (2020). Figure A.8 displays cooling energy intensity (Wh/CDD/ft^2) for the study and RECS mobile homes. MH2 continues as an outlier but this time because its cooling intensity is zero.

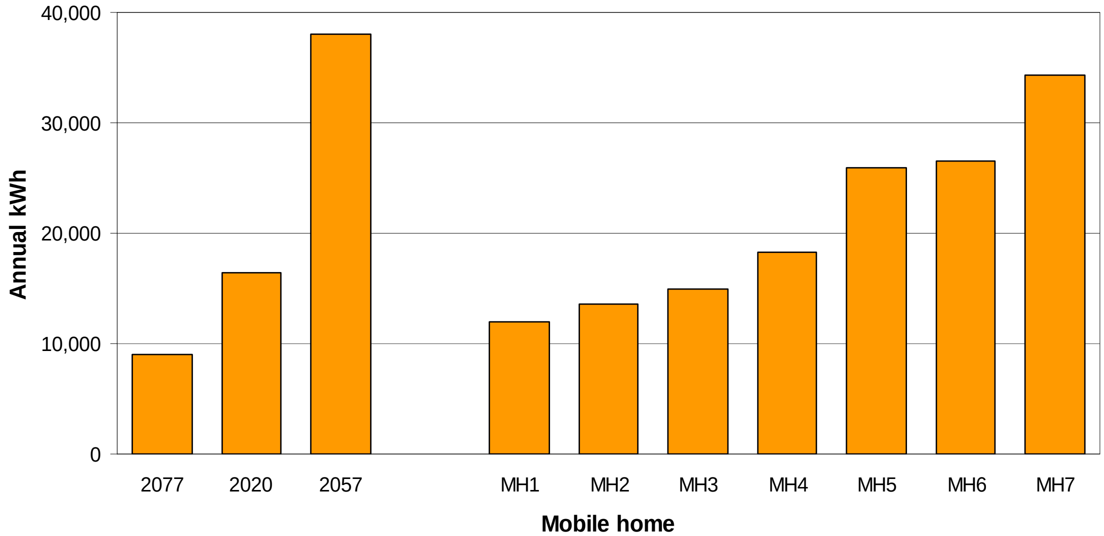

Figure A.5. Annual electricity use of all-electric study and RECS mobile homes. Study mobile homes are labeled 20##. RECS mobile homes are labeled MH#.

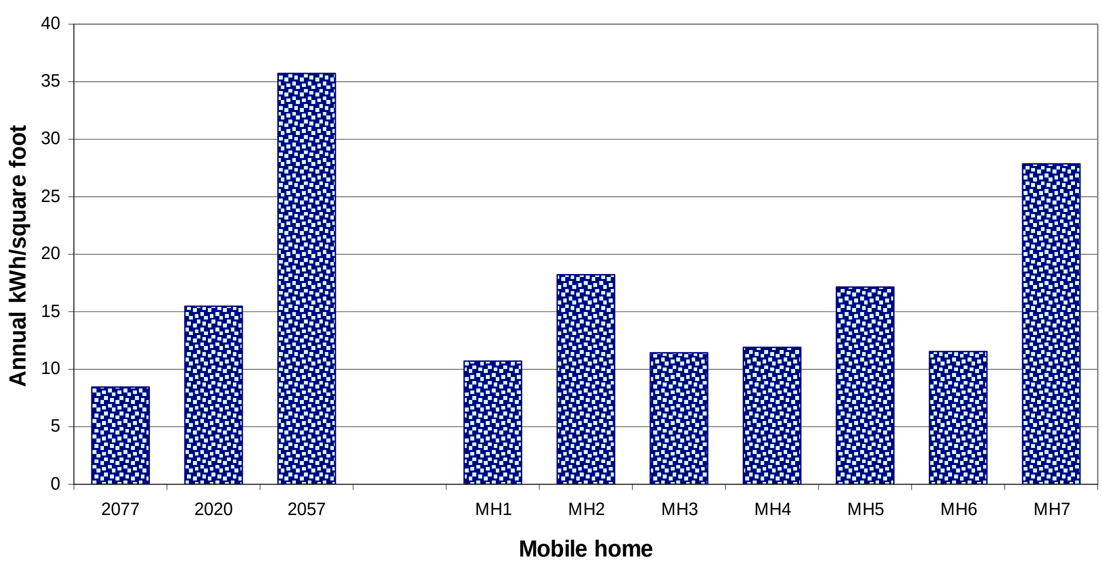

Figure A.6. Household energy intensity of all-electric study and RECS mobile homes. Study mobile homes are labeled 20##. RECS mobile homes are labeled MH#.

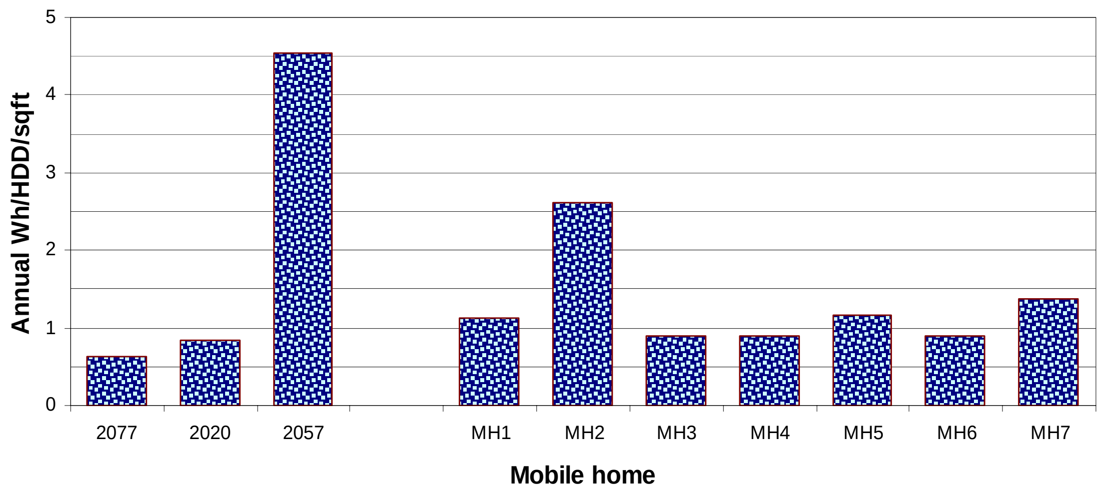

Figure A.7. Heating energy intensity of all-electric study and RECS mobile homes. Studv mobile homes are labeled 20##. RECS mobile homes are labeled MH#.

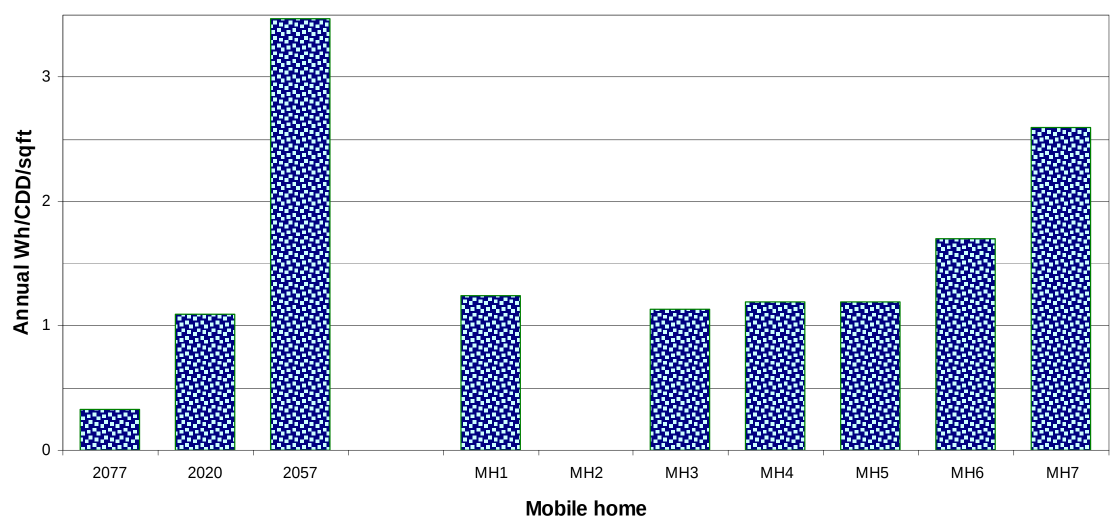

Figure A.8. Cooling energy intensity of all-electric study and RECS mobile homes. Study mobile homes are labeled 20##. RECS mobile homes are labeled MH#.

A.3 DISCUSSION

Comparison of the study single-family detached houses and mobile homes with similar RECS dwellings shows that the two groups have similar patterns of electricity use. Based on these small samples, there is no reason to suspect that the study houses are significantly different than low-income homes in comparable climates studied for the RECS survey.

The striking finding is the high level of diversity of electricity use patterns found in both groups. Figures A.1 and A.5 show that total annual electricity use varies by factors of 5 to 6 for single-family houses and of 3 to 4 for mobile homes.

Figures A.2 and A.6 show that adjusting for house size does not eliminate the variability. Focusing on heating energy use and adjusting for climate as well as house size (Figs. A.3 and A.7) reveals variations even larger than those in heating energy intensity than in total annual electricity use. Cooling energy use adjusted for climate and house size again reveals even larger variations. Evidently, occupant behavior or other factors play a large part in the variability.

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