LBL-28147 Vol. I
UC-350

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE
DIVISION

Measured Energy Savings and Economics of Retrofitting Existing Single-Family Homes: An Update of the BECA-B Database

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February 1991

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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL--28147-Vol.1

DE92 000689

MEASURED ENERGY SAVINGS AND ECONOMICS OF RETROFITTING EXISTING SINGLE-FAMILY HOMES: AN UPDATE OF THE BECA-B DATABASE

Volume I

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The work described in this report was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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EXECUTIVE SUMMARY

The energy bill for U.S. single-family households was over $77 billion in 1987 (excluding auto fuel purchases), accounting for approximately 20% of national energy expenditures. Large sums are spent on residential retrofits by individual homeowners, government agencies, and utilities. As of late 1987, over 21 million households indicated that they had added at least one energy-saving measure in the previous two years, while a recent Electric Power Research Institute (EPRI) study estimated that nearly 15 million residential customers have participated in some kind of demand-side management (DSM) program. Given the level of continuing investments in residential energy efficiency, accurate estimates of savings from various conservation measures are increasingly necessary, especially as new technologies become more sophisticated and incremental efficiency gains more difficult to achieve.

This report provides a comparative analysis of *measured* data on the performance and cost-effectiveness of energy-saving measures in existing single-family homes, based on information in the Buildings Energy-Use Compilation and Analysis (BECA) data base. The initial BECA report on measured data for single-family retrofits was completed seven years ago (Goldman 1984). In updating the single-family database, we have added 135 data points, representing over 33,000 houses, to the original database of 145 retrofit projects. The report is organized in two volumes. Volume I provides a summary of energy savings and costs of individual retrofit measures and strategies and results from federal/state low-income and utility weatherization programs. We also discuss measurement issues, predicted versus actual savings, trends in single-family retrofit programs, and implications for the "next generation" of cost-effective single-family retrofits. Volume II contains a written summary of each retrofit project and complete data tables.[1]

Savings and Costs for Individual Retrofit Measures

Table ES-1 summarizes the range in average values reported in various retrofit projects for energy savings, costs, and the cost of conserved energy (CCE) of individual retrofit measures (see Chapter 4). With a few exceptions (e.g., attic insulation and air conditioner replacement), these projects mostly involve homes that are located in colder climates (>5000 heating degree days (HDD)) and use gas for space heating. The results indicate that attic and wall insulation (especially high-density wall insulation that also seals air leaks), flame retention burners for oil furnaces, infiltration reduction guided by blower-doors, power gas burners, and low-cost water heater measures are cost-effective retrofits. These retrofits are economically attractive relative to average residential gas ($6.00/MBtu) and electricity prices (7¢/kWh) in the U.S. Condensing furnace replacements saved 27-39 MBtu/year in four studies and appear to be marginally cost-effective in more severe heating climates (>5500 HDD), even if the entire cost of the retrofit is attributed to energy efficiency. However, in many instances, the existing furnace is at the end of its useful life and needs replacement anyway in which case the economic analysis should be based on the incremental cost and energy savings between a high-efficiency model and a new

[1] Note that many retrofit projects are summarized in volume II that are not discussed in this report.

baseline model. In this situation, we estimate that the incremental savings are typically about 50% of total savings, while incremental costs are about $500. Using these assumptions, the CCE for heating system replacements in these regions are much more attractive, ranging between $2-3/MBtu (see Chapter 4). Replacing existing air conditioners with high-efficiency models can be cost-effective when the unit is due to be retired, but (as Table ES-1 shows) until that time equipment replacement is often not cost-justified based on energy savings alone. The effects of foundation insulation for unconditioned basements in Minnesota homes were documented in two R&D studies. Average gas savings were greater in homes that installed interior foundation insulation compared to homes that received exterior insulation. A study in Manitoba found significantly larger savings for foundation insulation in conditioned basements.

Table ES-1. Savings and economics of individual retrofit measures.[a]

	Number of Retrofit Projects (Homes)	Average Savings of Main Space Heat Fuel (MBtu/yr)	(%)	Average Retrofit Cost (1989 $)	Avg. Cost of Conserved Energy (CCE) (1989 $/MBtu)
Ceiling Insulation	7 (33,300)	13-31	12-21	500-970	1.80-4.40
Wall Insulation	3 (27)	19-44	12-17	810-1600	1.60-6.90
Foundation Insulation in *Unconditioned* Spaces					
- Interior (R-0 to R-14)	2 (17)	6-20	6-15	1040-1200	5.00-17.70
- Exterior (R-0 to R-10)	2 (11)	2-11	3-10	1340-1710	12.00-67.00
Foundation Insulation in *Conditioned* Spaces					
- Interior (R-0 to R-11)	1 (24)	32	-	1020	3.00
Replacement Windows	2 (130)	2-5	-	940-3350	16.50-190.00
Oil Flame Retention Burners	3 (187)	20-32	14-25	460-570	1.90-2.90
Power Gas Burners	2 (30)	10-11	6	560	5.40-6.40
Heat Extractor (condensing)	1 (88)	7-19	4-14	720	5.40-16.00
Condensing Furnaces	4 (85)	27-39	19	1880-4750	4.80-12.00
(Est. Incremental Savings & Costs)[b]	"	14-20		500	2.20-3.00
Central A/C Replacement	1 (12)	2130 kWh	12	2760	14¢/kWh
Water Heater Wrap	1 (20)	970 kWh	-	22	0.4¢/kWh

[a] Range in average values for energy savings, retrofit costs, and CCEs are reported for retrofit projects with results from individual measures. The CCE is calculated using a 7% discount rate. Savings refer to all enduses of the main space heating fuel (e.g. typically space heating, water heating, and cooking).

[b] We assumed that incremental savings were 50% of total savings and calculated the CCE using a 25-year measure lifetime (see Chapter 4).

Federal/State Low-income Weatherization Program

The state-of-the-art in weatherizing homes has improved dramatically in the last fifteen years, due in part to continued monitoring and program evaluation efforts in a few cold-climate states. A national evaluation of the 1981 DOE Weatherization Assistance Program showed average savings of the space heat fuel of 14 MBtu/house (10% of the normalized annual consumption (NAC)), at a cost of conserved energy (CCE) of $11/MBtu (Table ES-2). Twelve state evaluations of post-1980 weatherization programs show median savings of the space heat fuel (NAC) of 12% (range of 7-14%) despite relatively low levels of pre-retrofit energy use. The median retrofit cost was $1080 (1989$) and the median cost of conserved energy was $6.80/MBtu. However, the median CCE is lower for the five cold climate states that have conducted weatherization evaluations since 1985. This improved cost-effectiveness occurs in part because several of these states have incorporated lessons learned from previous program evaluations into their statewide program. Results from several recent demonstration projects are particularly encouraging and offer well-documented approaches for significant improvements in energy savings and cost-effectiveness of low-income weatherization in both cold and mild climates. For example, demonstration programs in Michigan and Minnesota in the last few years both achieved 18% NAC savings with CCEs of $3.60/MBtu and $5.90/MBtu respectively, despite particularly low levels of pre-retrofit consumption in the Minnesota homes (see Chapter 5). Average energy consumption decreased by 24 MBtu/year (16% of the NAC) with a CCE of $4.50/MBtu in 43 Virginia homes that participated in a pilot demonstration that utilized a new weatherization protocol. The protocol emphasized wall and ceiling insulation, and blower-door guided sealing of the foundation area and attic bypasses.

Table ES-2. Savings and economics of low-income and utility weatherization programs.

	Number of Retrofit Projects (Homes)	Average Energy Savings of Space Heat Fuel (MBtu/yr)	(%)	Average Cost (1989 $)	Avg. Cost of Conserved Energy (1989 $/MBtu)
Low Income Weatherization					
1981 National	1(965)	14	10	1380	11.00
Post-1980 State Evaluations	12(3800)				
Median Value		19	12	1080	6.80
Range		7-23	7-14	810-2220	5.30-16.00
Optimal Weatherization Demo's	4(490)	24-45	-	980-2560	3.60-6.30
Targeted High Users	4(240)	21-95	9-25	670-4040	4.00-5.70
Utility Weatherization					
Gas Utilities					
Pre-1980 Programs	5(33200)	12-33	6-21	500-700	1.80-4.40
Post-1980 Programs	5(16800)	5-33	8-19	570-3800	5.00-11.00
Electric (Pacific NW)[a]					
Median Value	21(12700)	4020 kWh	16	2150	5.4¢/kWh
Range	20(12400)	2000-8600 kWh	8-26	640-2800	1-15¢/kWh

[a] Results are gross (not net) savings. Range values exclude 1986 Seattle City Light HELP program (see Chapter 6).

Manufactured ("mobile") homes account for about ten percent of the single-family homes eligible for federal low-income weatherization funds. At present, most programs that weatherize manufactured homes typically attempt to use the same retrofits as for site-built homes, rather than developing specialized techniques adapted to manufactured housing materials and construction practices. Consequently, average weatherization savings tend to be much lower than for site-built homes, while retrofit costs are comparable. Recommended measures for manufactured homes include belly insulation and the use of blower doors to guide envelope and duct system infiltration reduction. Additional field demonstrations are needed to demonstrate which measures and techniques are the most cost-effective for retrofitting manufactured homes.

Retrofit savings and cost-effectiveness of the low-income weatherization program could be improved nationally if techniques from the more advanced state programs and demonstration projects are adopted by weatherization agencies in other states. Results reported in the BECA data base represent a relatively small subset of all state low-income weatherization programs--those that have published measured data. The relative energy savings (i.e., percentage reductions) and cost-effectiveness of weatherization programs in other states may be worse; those states that do not conduct monitoring or evaluation also tend to run less sophisticated programs and lack the advantage of feedback from measured results. In these other states, anecdotal evidence suggests that significant improvement is possible in program performance based on current practices. For example, in some states, a limited list of measures is uniformly installed whenever applicable in each house. Retrofit strategies are not adapted to accommodate differences in residential building types (e.g., site-built vs. manufactured homes and large multifamily buildings). Newer techniques that improve the effectiveness of such measures as bypass sealing and wall insulation appear to be utilized infrequently. Finally, many states do not conduct periodic evaluations based on metered data, a process which can be used to refine and improve program design and implementation. Based on the regional distribution of evaluations that have been published, there is a particular need for high-quality monitoring and evaluation of weatherization programs in mild or cooling climates.

Utility Weatherization Programs

Over the past ten or more years, an ever-increasing number of electric and gas utilities have provided financial incentives and other services to their single-family residential customers. Prior to 1981, most weatherization programs implemented by gas utilities emphasized insulation of uninsulated attics and were open to all residential customers. More recent programs with measured data have focused on low-income households and have sometimes been less concerned with cost-effectiveness. Table ES-2 illustrates this trend. Earlier programs produced larger energy savings (though similar percentage savings) at lower unit costs of conserved energy. An expanded list of retrofit measures--including major equipment retrofits or replacements in cold-climate areas--has also contributed to the higher costs. Gas utility programs are likely to be expanded in the next few years, as supplies tighten and state regulatory agencies place increased emphasis on cost-effective conservation.

This trend is already in evidence for electric utilities, particularly in regions where hydro power has historically provided low-cost electricity to residential customers. In the Pacific Northwest, about 340,000 homes have already been retrofitted, with nearly the same number remaining to be weatherized. Table ES-2 shows the results for 21 programs in this region. Pre-retrofit electricity use was high (21,000-33,000 kWh/year). Median electricity savings of 4020 kWh/year (16% of the NAC) were achieved at a median cost of conserved energy of about 5.4¢/kWh.

The Hood River demonstration project was an important exception to the high pre-retrofit consumption common in most Pacific Northwest programs. This program was designed to test the potential for "saturation" retrofit of an entire community and consequently measures were offered at no cost to homeowners. Costs averaged $6100/house and average savings were 4000 kWh (16% of the NAC), giving a CCE of about 14¢/kWh. Cost-effectiveness might have been improved if some marginal measures had not been included in this saturation effort. Sub-metering of space heat and other end-uses showed that post-retrofit heating energy intensity in the Hood River homes averaged 2.6 Btu/ft^2-HDD,[2] which might be considered a benchmark for other retrofit programs targeted to single-family, electrically heated homes.

A few utilities have continued to monitor the persistence of energy savings, based on several years of post-retrofit data. We examined results from up to six years of post-retrofit consumption from the 1981-87 Seattle City Light HELP program and several evaluations of the Bonneville Power Administration weatherization program that included three years of post-retrofit data. We found that average electricity consumption for participating households remained stable during the first several years after retrofit and that gross savings appear to be maintained. Net savings, which adjusts overall savings for changes in consumption of a control group of non-participants, are much more volatile over time and across different periods, because of householders' behavior in response to changing electricity prices and perhaps other factors. Additional survey data coupled with field measurements (beyond the level of whole-house utility bills) are needed to better understand the relationship of physical performance and occupant behavior, as they affect energy savings over the expected lifetime of a conservation measure.

Predicted vs. Actual Savings

About 20% of the single-family data points in the BECA compilation include data on predicted as well as actual energy savings (Chapter 7). Prediction methods ranged from simple engineering heat-loss calculations and default values to building energy simulation models. The median reductions in the electricity consumption of groups of participating homes were 63% of predicted estimates in nine weatherization programs sponsored by electric utilities. The variance in results was quite large (i.e., the ratio of actual to predicted savings ranged from 50-157% percent). The median value was 75% for 12 R&D projects that tested various retrofit options (foundation and wall insulation, house-doctoring) in gas-heated homes. The agreement between actual and predicted estimates was somewhat better among 12 retrofit projects that focused only on

[2] Calculated as site energy (3412 Btu/kWh).

changes in space heating usage (median within 15%). Most of the projects in this last group were also R&D studies, which tended to have somewhat more accurate predictions, either because of better input data and models and more experienced users, or because the predictions were made "after the fact" (with known pre- and post-retrofit energy use) rather than "blind" (see Chapter 7 for more detailed discussion). Retrofit savings predictions are likely to continue to improve, as energy audit methods become more sophisticated and data on actual measured savings are fed back into the auditing and analysis process.

Research Needs and Future Work

Data collected since the last BECA-B update in 1984 have begun to fill many gaps in our understanding of cost-effective ways to save energy in single-family homes. However, more and better data and analyses are needed on improved techniques for retrofitting manufactured housing, cooling retrofits, impacts of retrofits on peak electricity demand, reduction of losses from duct work, effects of occupant behavior on energy savings (and persistence), submetering of measures that produce small savings but may still be cost-effective, and retrofit performance in mild and cooling climates.

1. INTRODUCTION

Energy efficiency in existing homes, after several years of relative neglect, is getting increased attention from households concerned with rising fuel and electric bills, utilities newly attuned to energy savings as a demand-side resource, and government policy-makers at all levels, who are beginning to address potential supply constraints and the impacts of energy production and use on environmental quality and global climate change. After more than a decade of little or no net growth in energy use, despite significant gains in the GNP and building stocks, total energy use in the United States increased by 9.4% between 1986 and 1989 (from 74.2 quads to 81.2 quads) (EIA 1990). Single-family residences are an important component of national energy use. In 1987, 65.5 million single-family homes in the United States used 670 billion kWh of electricity and nearly 5 quads (1 quad = 10^{15} Btu) of fuel, representing about one-sixth of total end-use energy (EIA 1989b). The total energy bill to U.S. single-family households was over $78 billion in 1987 (excluding auto fuel purchases), accounting for 20% of national energy expenditures.

Large sums are spent on residential retrofits by individual homeowners, government agencies, and utilities. As of late 1987, over 21 million households indicated that they had added at least one energy-saving measure in the previous two years (EIA, 1989). Nearly 15 million residential customers are participating in some kind of DSM program (EPRI 1990). From 1981 to 1989, the Bonneville Power Administration spent $427 million on weatherization programs (BPA 1990). Between 1984 and 1986, residential programs conducted by California utilities improved the efficiency of fifteen percent of the state's housing stock (Calwell and Cavanagh 1989). Finally, from 1977 through 1989, the Federal and state governments spent about $2.4 billion to weatherize low-income houses, under a variety of programs (Schlegel, McBride, and Thomas 1990). Given the level of continuing investments in residential energy efficiency, accurate estimates of savings from various conservation measures are increasingly necessary, especially as new technologies become more sophisticated and incremental efficiency gains more difficult to achieve.

Most estimates of energy savings from residential retrofits are still based on engineering calculations, computer simulations, or professional judgment, rather than measured data. A compilation of measured data on both energy performance and cost-effectiveness can provide an empirical benchmark for these estimates, improve their credibility, and help identify selected issues that require additional measurement and analysis. Due to the high cost of field measurements, sample sizes are generally small. Lack of standard measurement and reporting procedures often make it difficult to compare results among individual studies.

This study provides a comparative analysis of measured data on the performance and cost-effectiveness of energy-saving measures in existing single-family homes, based on information in the Buildings Energy Use Compilation and Analysis (BECA) data base.[3] The initial BECA

[3] The BECA data base now contains over 3000 records; most of these are for U.S. buildings. Components of the BECA database include data on new, low-energy homes (BECA-A); retrofits of existing residential single-family and multifamily buildings (BECA-B); new, energy-efficient commercial buildings (BECA-CN); retrofits of existing commercial buildings (BECA-CR); load management strategies in commercial buildings (BECA-LM); and residential water heating systems (BECA-D) Reports on each compilation are available through the Energy Analysis Program at Lawrence Berkeley Laboratory (415-486-7288).

report on measured data for single-family retrofits was completed seven years ago (Goldman 1984). In updating the single-family database, we have added 135 data points, representing over 33,000 houses to the original database of 145 retrofit projects.[4] The data points represent aggregate results from studies that report on metered savings and costs of individual retrofit options or evaluate packages of measures installed as part of low-income or utility weatherization programs. Since the last update, the breadth and quality of data available on individual retrofit options has improved significantly. For example, in our previous study, the only measured data from occupied houses on individual retrofits were for ceiling insulation and flame retention burners. In this report, we discuss savings from 14 individual retrofit measures. These new studies help fill in longstanding gaps in our understanding of retrofit performance.

There have also been major changes in weatherization programs and notable improvements by some states and utilities in techniques used to evaluate actual program impacts. For example, the list of eligible measures for DOE's low-income Weatherization Assistance Program was expanded in the mid-1980s to include heating and hot water system equipment retrofits in addition to the list of traditional shell measures. Program delivery and administration guidelines were also changed (e.g., higher cost limits per house, revised rules for working with owners of multifamily buildings with many low-income tenants). Moreover, a number of states have conducted comprehensive and well-documented evaluations of their low-income weatherization programs. Improved monitoring and analysis techniques are being used to provide more accurate savings estimates. Almost all new evaluations make some type of correction for outside temperatures and include control groups; a few have measured changes in inside temperature and/or submetered space heat energy.

This report is organized in two volumes. Volume I provides a comprehensive summary of overall results, while Volume II includes technical appendices and detailed written summaries and data tables for each retrofit project. The remaining Chapters of Volume I discuss the following topics. Chapter 2 describes sources of data and the types of information collected while Chapter 3 provides a summary of the methods used to analyze and normalize energy consumption and savings, adjust retrofit cost data, and calculate economic indicators. In Chapter 4, we discuss the performance of individual retrofit measures, including wall, foundation, and ceiling insulation, window replacements, furnace and air conditioner replacements, heating system retrofits, house-doctoring, warm-room zoning, and water heating measures. Results from both Federal/state low-income weatherization and utility-sponsored programs are examined in detail in Chapter 5 and 6, along with a discussion of recent trends to put these findings in context. Chapter 7 discusses and compares predicted versus actual savings for a sub-set of retrofit projects in the database that included estimates of savings. In Chapter 8 we discuss implications for future retrofit potential in the single-family housing stock.

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[4] We also reviewed and, in some cases, updated the original studies, where additional information was available (e.g., data on persistence of savings). A few retrofit projects were deleted from the database because they no longer met the revised guidelines on minimum data quality.

2. DATA SOURCES AND QUALITY

The BECA project relies on monitored performance data collected by others. We obtain data on the measured performance of retrofits in single-family buildings from a variety of sources: literature reviews, conference proceedings and journals, the trade press, and contacts with program managers and researchers. Potential data sources are screened and those projects (or certain houses in a study) that do not meet minimum data quality standards are eliminated (e.g., houses must have a continuous billing history that includes the heating season and preferably one year of data before and after retrofit). Projects are screened to assure that savings are related to the actual retrofit. For example, we eliminate households that use wood or other non-metered fuels for space heating or had occupancy changes during the study period. In some cases, we also perform additional analysis of the original data from a retrofit study, particularly in cases where we attempt to isolate the effects of individual measures. Where necessary, reported energy consumption and savings data are adjusted to normalized weather and operating conditions, and retrofit costs are estimated in cases where only materials costs are given. Any adjustments to the original data or results that are made by Lawrence Berkeley Laboratory (LBL) are indicated in the description of individual projects (see Volume II, Appendix B).

In most cases, a retrofit "data point" represents aggregate results from a group of houses, although sample sizes vary significantly. Sample sizes tend to be small for research and demonstration (R&D) projects, typically ranging from 5-30 houses at a particular location. In contrast, evaluations of utility and low-income weatherization programs often report aggregate results from thousands of households. Reliability of energy savings from individual measures or retrofit strategies is often quite robust in R&D studies, despite the relatively small sample sizes, because of more comprehensive monitoring of energy consumption and control of other factors that could affect savings estimates. More recent R&D projects often include submetered energy use and monitored indoor temperatures. In contrast, program evaluations typically rely only on whole-house energy data from utility bills. There is a general trend toward improved data quality and experimental design in recent program evaluations, as evidenced by the widespread use of control groups, detailed household surveys of customer behavior and building characteristics, and more complete data on program and customer costs.

We collect information on retrofit measures, installed costs, and metered pre- and post-retrofit energy consumption. Data are entered in a computerized data base and each retrofit project is described in a written summary (see Volume II). We also seek more detailed information on the physical and demographic characteristics of participating households (e.g., average house size, insulation and glazing levels, type and efficiency of heating system, and the average number of occupants). We assign each project a confidence level for two data categories: energy consumption and retrofit costs. Confidence levels for specific projects are listed in Appendix A, along with the rating criteria. Only 4% of the projects are rated "A" in both categories, indicating a detailed breakdown of costs for each individual measure and sub-metered energy use data. About one-third of the projects in the database are rated "B" or higher in both categories, indicating, at a minimum, complete utility billing data and contractor costs. The quality of available data has improved compared to our earlier compilation.

3. METHODOLOGY

Figure 1 provides a flow chart of the analytic steps that are used to compile and compare results of individual retrofit projects. Average and median energy savings are calculated for participating households. In addition, we collect information on retrofit costs and energy prices and calculate various cost-effectiveness indicators using a specified discount rate (7% real) and standard economic lifetimes for measures and programs (see Table 1). Much of our effort is devoted to comparative analysis in which we examine similar types of retrofit projects and attempt to determine the most cost-effective individual measures and retrofit strategies. Our conclusions are based on R&D studies, as well as the performance of packages of measures based on program evaluation results. We also provide data contributors with feedback: a written and tabular summary of results, which is used to verify and revise our analysis (if necessary) along with comparisons of similar retrofit efforts. In the next sections, we briefly describe the approach used to analyze household energy consumption data and calculate savings, adjust retrofit cost data, and calculate economic and building performance indicators. Volume II includes a more detailed discussion of methodology.

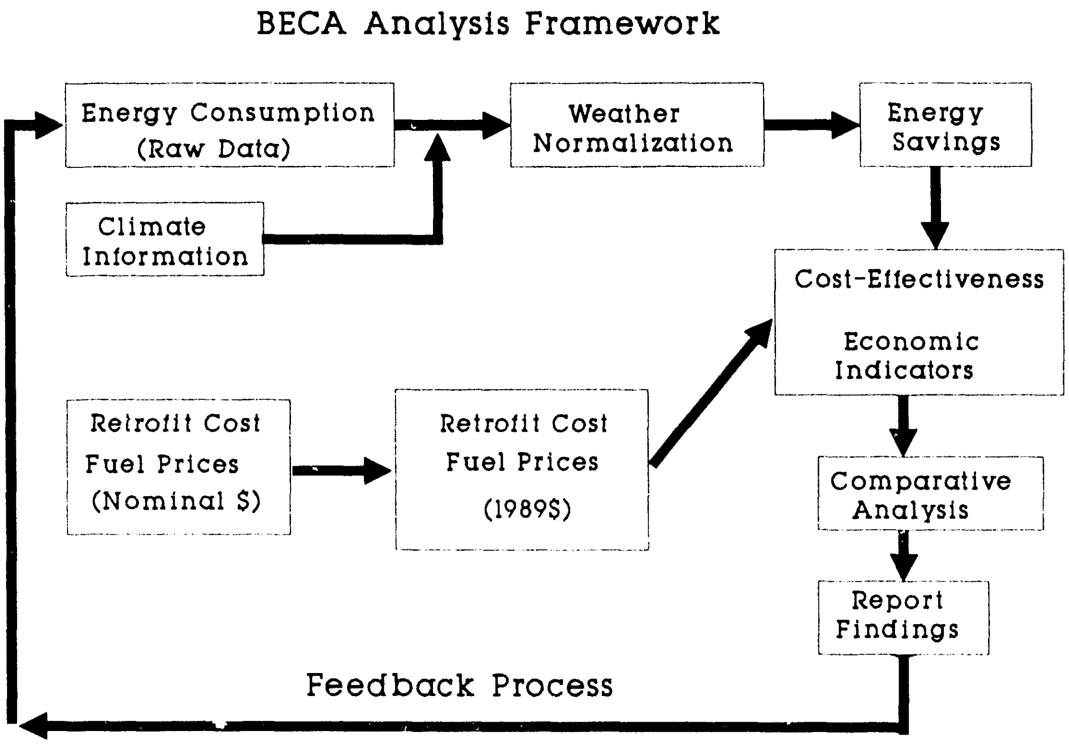


Figure 1. Overview of analytical steps used in the BECA-B project to compile and perform comparative analysis on technical and economic performance of retrofit measures/strategies in single-family buildings.

Table 1. Retrofit Measure Lifetimes.

Retrofit Measure	Lifetime (yrs)
Individual Measures	
Attic Insulation	20
Foundation Insulation	20
Wall Insulation	25
Insulating blanket on Hot Water Heater	7
Storm Windows	15
Window Replacements	20
Storm Doors	10
Door Replacements	20
Heating System Retrofits	10-15
Furnace replacement	25
Caulking + Weatherstripping	5
Measures associated with 'House-Doctoring'	10
Set of Measures installed in Various Programs	
DOE Low-Income Weatherization	15-20
Utility-sponsored Programs	15-20

3.1 Energy Savings

The quality of energy data vary widely. About 30% of the data points are from projects with submetered data, about 45% have monthly utility bills for at least one year before and after the retrofit was installed, while for 20% of the projects the only information available is annual energy use. (Submetered data represent a large number of data points, but a comparatively small number of houses). Most studies screened for auxiliary space heating fuels, either explicitly or statistically. Some studies queried the occupants, others required a R^2 correlation > 0.8 from PRISM analysis. (A high correlation between the use of the main space heating fuel and heating degree days implies that there is no significant use of an auxiliary heating fuel.) Few studies corrected for differences in internal gains or indoor temperature settings.

For most of the buildings, the Princeton Scorekeeping Method (PRISM) was used to weather-normalize whole-building energy consumption data before and after retrofit (Fels et al. 1986). For gas-heated buildings, the end uses included in the normalized annual energy consumption (NAC) were typically space heating, water heating, and cooking. Most of the electric-heat buildings were all-electric so the NAC includes all household end uses. The NAC represents consumption that would occur in a year with typical weather conditions.

In cases where only seasonal or annual energy consumption data were available, LBL (or the original authors) corrected for the varying severity of winter in different years by scaling annual estimated space heating energy use by the ratio of normal-year to actual-year heating degree days (base 65° F).

3.2 Gross versus Net Energy Savings

In reporting energy savings, two methods are used. Gross savings are the actual savings of the retrofitted homes. Net savings are adjusted for changes in a control group in order to correct for factors other than the retrofits that could affect changes in consumption over time (e.g., response to rising energy prices, increased saturation of home electronics). About 45% of the projects in the BECA-B compilation include a control group. Thus, calculating net energy savings relative to a control group could not be uniformly implemented. Even among those projects that employed control groups, there were significant differences in terms of method of selecting control groups, the control group's knowledge of the experiment, and level of retrofit activity independent of the program. For example, in many R&D studies, a control group is intended to isolate the performance of the retrofit measure(s). Households in the control group are asked not to install any retrofit options during the period of the study. Thus, any adjustments to savings from the test group are designed to isolate the actual savings attributable to retrofit measure(s). In contrast, in many utility program evaluations, control groups are utilized to capture broader trends in energy consumption over time in response to price and other key factors. The objective in these program evaluations is to determine savings that can be directly attributed to the utility program, as opposed to performance of specific measures. It is assumed that households in a control may install retrofit measures or adjust their energy-using behavior in response to significant price increases. These differences between R&D studies and utility program evaluations tend to argue against uniform treatment of control group results.

In this study, we report both gross and net savings. Given that our primary objective is determining savings associated with a set of measures (rather than program impacts), we tend to rely on gross savings, particularly in interpreting the results of program evaluations. Unless otherwise indicated, savings should be interpreted as gross savings and these savings values are used in the economic analysis.

3.3 Retrofit Costs, Economic Indicators, and Measure Lifetimes

Retrofit costs reported in this study reflect direct costs to the homeowner of contractor-installed measures. Program costs include labor and materials, but not administrative costs. We adjusted actual retrofit costs to costs in 1989 dollars using the GNP Implicit Price Deflators. Two economic indicators were calculated to characterize the cost-effectiveness of retrofit investments: simple payback time (SPT) and cost of conserved energy (CCE).

SPT is defined as:

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

where:

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

Simple payback time is a commonly used indicator of retrofit cost-effectiveness; it is familiar and easily understood by homeowners and program managers. However, the SPT does not reflect differences in useful lifetimes beyond the payback date or incorporate the time value of money.

We also calculate the cost of conserved energy (CCE), which can be used to compare conservation investments to purchases of fuel or electricity. The CCE takes into account differences in expected retrofit lifetimes, which the payback time does not. The other advantage of CCE is that it is independent of current energy prices. CCE is found by dividing the annualized cost of the retrofit by the annual energy savings. A retrofit is cost-effective if the CCE is less than the price of energy. It can be expressed as:

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

where:

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

RC	= Retrofit cost (in current dollars)
d	= discount rate
n	= lifetime of measures

Conservation investments are amortized over the measures' expected physical lifetimes, using a real (i.e., constant dollar) discount rate of seven percent. Although expected lifetimes of retrofits are difficult to define, we believe that the use of a consistent source of retrofit lifetimes allows a fair comparison of retrofit cost-effectiveness. Since estimates of retrofit lifetime vary widely, we developed a standard list of lifetimes for programs and measures based on a review of the literature (see Table 1). For sets of measures, the lifetime is weighted by expected savings.

For heating system retrofits, the lifetime may be determined by the remaining useful life of the furnace, not the actual retrofit measure. The range of 15-20 years for weatherization measures is intended to account for the range of measures as well as the condition of the housing stock that is being retrofitted. We assign a 20 year lifetime to programs that install high saturations (>50%) of both wall and ceiling insulation.

4. INDIVIDUAL RETROFIT MEASURES AND STRATEGIES: SAVINGS AND COSTS

4.1. Overview

In this chapter, we present results on the energy savings and economics of individual measures and retrofit strategies. Most of the data are from research and demonstration (R&D) projects monitoring gas-heated homes located in cold climates. Increasingly, field research projects are beginning to move beyond whole-house utility billing data and make use of continuous, on-site monitoring equipment to measure energy by end-use, indoor temperatures, and sometimes other variables (e.g., equipment status, HVAC flows and temperatures). This level of monitoring is often essential to quantify the effect of individual measures, especially where expected savings are a relatively small fraction of total energy use (less than 5% for typical sample sizes). However, most studies in our database still rely on whole-house utility billing data. Low-cost measures that save small amounts of energy may be very cost-effective, but given the level of existing data, we are unable to determine energy savings for these measures.

It is also worth noting that costs reported in R&D studies tend to be high because cost minimization is often not a primary consideration. The measures are typically being installed in small-scale programs so volume discounts are not available. New technologies, by definition, have small market shares, and thus it is difficult to capitalize on economies of scale. Finally, costs may be high because installation techniques have not had a chance to improve over time. Actual retrofit costs from R&D studies are used in our economic analysis, although we highlight cases in which contractor-installed costs are likely to be much lower in large-scale programs and, in some cases, we provide estimates of these costs.

Energy savings, retrofit costs, and cost-effectiveness for all individual retrofits are are summarized in Table 2 and described in detail in the following sections. Key findings are:

- Ceiling and wall insulation were quite cost-effective, with NAC savings ranging between 12-21% in 10 retrofit projects, and average CCEs between $1.60-$6.90/MBtu.
- Measured data on savings and economics of foundation insulation is drawn from three studies in severe heating climates (>8000 HDD). Results were were mixed, depending to some extent on retrofit technique (i.e., interior vs. exterior) and basement condition (unconditioned vs. conditioned), although payback times were generally quite long.
- Window replacements were found to have small savings (2-5%) and not particularly cost-effective (CCE > $15/MBtu).
- Flame retention burners for oil furnaces produced significant savings (20-32 MBtu/year for the three studies in our data base) and had CCEs of less than $3/MBtu.
- Several retrofit strategies that improve the efficiency of gas furnaces produced annual savings ranging between 6-19 MBtu/year (4-14%), with CCEs that were comparable to current gas prices ($5-7/MBtu). Condensing furnace replacements saved 27-33 MBtu/year in the three U.S. studies and appear to be marginally cost-effective even if the entire cost of the retrofit is attributed to energy efficiency. Water heating retrofits appear to highly cost-effective.

Table 2. Average savings and economics of individual retrofits.

Measure	Label	Data Source	Prog. Type	Yr	Number of Homes	State(HDD)	NAC pre (MBtu)	Average NAC Savings (MBtu)	Average NAC Savings (%)	Cost (1989$)	SPT (yrs)	(1989$/ MBtu)
Shell Measures												
Ceiling insulation (to R-30)	G030	Consol. Gas	U	73	71	MI (6300)	235	31	13	630	4	1.80
" (R-11 to R-30)	G013	Public Serv. Co.	U	77	33,000	CO (6000)	157	20	13	500	6	2.40
" (R-14 to R-31)	G028.1	Univ. of Illinois	R	78	5	IL (5800)	169	28	17	970	5	3.20
" (R-0 to R-19)	G012.1	PG&E	U	79	33	CA (2200)	117	15	13	690	6	4.40
" (R-0 to R-19)	G012.2	PG&E	U	79	16	CA (2700)	95	20	21	680	4	3.30
" (R-11 to R-40)	M028.3	Manitoba E&M	L	84	47	CAN(10600)	-	21	-	660	8	2.90
" (R-values unknown)	G061.4	Battelle	U	87	162	OH(6000)	111	13	12	-	-	-
Wall insulation	G052.4	CEUE	L	82	8	MN (8000)	168*	20	12	1600	11	6.90
"	G066.4	Int'l Energy	W	84	7	WI (7500)	115*	19	17	810	6	3.60
"	M028.4	Manitoba E&M	L	84	12	CAN(10600)	-	44	-	850	5	1.60
Foundation insul. in *unconditioned* spaces												
Interior foundation insul. (R-0 to R-11)	G051.1	CEUE	L	84	8	MN (8000)	129*	20	15	1040	8	5.00
" (R-0 to R-14)	G067.1	Robinson Tech.	R	88	9	MN (8000)	112*	6	6	1200	33	18.00
Exterior foundation insul. (R-0 to R-10)	G051.2	CEUE	L	84	5	MN (8000)	110*	11	10	1340	19	12.00
" (R-0 to R-10)	G067.2	Robinson Tech.	R	88	6	MN (8000)	87*	2	3	1710	127	67.00
Foundation insul. in *conditioned* spaces Interior foundation insul. (R-0 to R-11)	M028.5	Manitoba E&M	L	84	24	CAN(10600)	-	32	-	1020	8	3.00
Replacement windows (R-values unknown)	M028.6	Manitoba E&M	L	84	89	CAN(10600)	-	5	-	940	49	17.00
	G078.3	Ball State Univ.	L	89	41	IN (5500)	112*	2	1	3350	450	190.00
Warm Room Zoning	G053.1	LBL	R	85	5	MO (5300)	170	48	28	1580	11	4.70
"	G068	NCAT	R	86	25	PA(5600)	137	31	23	2400	12	8.50
Heating System Retrofits												
Flame retention burners	O010.1	BNL	R	80	19	NY (5500)	-	22	14	460	2	2.90
"	O027.1	Mich PSC	R	84	76	MI (7000)	-	32	25	570	2	1.90
"	O026	PECI	R	85	92	OR (4700)	-	20	23	560	5	2.80
Power gas burners	G054.3	ASE/ORNL	R	85	16	KY (4500)	162*	10	6	560	11	6.40
"	G063.3	ASE/ORNL	R	85	14	MN (8000)	205*	11	6	560	10	5.40
Elec. vent damper and elec. ignition	G063.5	ASE/ORNL	R	85	42	MN (8000)	180*	6	4	440	14	10.00
Condensing heat extractors	G054.1	ASE/ORNL	R	85	43	KY (4500)	133*	19	14	720	7	5.40
"	G063.1	ASE/ORNL	R	85	35	MN (8000)	169*	7	4	720	23	16.00
Heating and Cooling System Replacements												
Condensing furnace replacement	G052.1	CEUE	L	82	3	MN (8000)	175*	33	19	4750	20(4)	12.00 (2.60)
"	G064.1	ORNL	R	85	3	WI (7500)	-	27	-	1880	9(5)	5.90 (3.20)
"	G079	Manitoba E&M	R	85	49	CAN (10,700)	-	39	-	2170	16(7)	4.80 (2.20)
"	G078.2	Ball State Univ.	L	89	30	IN (5500)	149*	29	19	2110	15(7)	6.20 (3.00)
Central air conditioner replacement	E034	Fleming Group	R	88	12	TX (2900 CDD)	-	2130 kWh	12	2760	13	[14¢/kWh]
Hot Water System Measures												
Water heater wrap	E033.1	ORNL	U	85	20	OR(5600)	-	970 kWh	-	22	0.5	[0.4¢/kWh]

Key for Table 2

Column	*Explanation*
2	Label - Summaries and data printouts are arranged by label in Volume II.
3	Data Source ASE = Alliance to Save Energy (Washington, D.C.) Ball State Univ. = Center for Energy Research/Education/Service and Department of Urban Planning, Ball State University (Cleveland, OH) Battelle = Battelle Inc. (Columbus, OH) BNL = Brookhaven National Laboratory (Upton, NY) CEUE = Center for Energy and the Urban Environment (Minneapolis, MN) (formerly the Minneapolis Energy Office) Consol. Gas = Consolidated Gas Company (Detroit, MI) Fleming Group = The Fleming Group (Syracuse, NY) Int'l Energy = International Energy Associates Limited (Portland, OR) LBL = Lawrence Berkeley Laboratory (Berkeley, CA) Manitoba E&M = Manitoba Energy and Mines (Winnipeg, Manitoba) Mich PSC = Michigan Public Service Commission (Lansing, Michigan) NCAT = National Center for Appropriate Technology (Butte, MT) ORNL = Oak Ridge National Laboratory (Oak Ridge, TN) PECI = Portland Energy Conservation, Inc. (Portland, OR) PG&E = Pacific Gas and Electric (San Francisco, CA) Publ. Serv. Co. = Public Service Company of Colorado (Denver, Colorado) Robinson Tech. = Robinson Technical Services (St Paul, MN) Univ. of Illinois = University of Illinois at Chicago
4	yr = Year of retrofit
5	Program Type L = State or city loan program R = Research or demonstration program U = Utility weatherization W = Low income weatherization
7	HDD = Heating degree-days (base 65°F)
8	NAC_{pre} = Weather-normalized annual consumption prior to retrofit. Projects that use PRISM in energy analysis are indicated by *.
9-10	Savings refers to the NAC of the main space heating fuel. For gas-heated homes, the end uses in the NAC include space heating and sometimes water heating and cooking.
11	Retrofit costs in 1989$. For central heating and cooling system replacements, the entire cost of the new unit is attributed to higher efficiency. For interior foundation insulation, the sheetrock costs are not included.
12	SPT = Simple payback time (calculated using local energy prices).
13	CCE = Cost of conserved energy (calculated using a 7% discount rate). For heating system replacements, the value in parentheses is calculated using the estimated incremental savings and incremental costs of the condensing model over a baseline model (see section 4.7).

4.2 Ceiling Insulation

Data on ceiling insulation retrofits come from evaluations of utility conservation programs in California, Colorado, and Michigan that were conducted in the early 1980s as well as several small research studies (Williams 1980; McLenon 1981; and Proudfoot 1979). The evaluations of utility-sponsored programs were relatively primitive by today's standards (e.g., no control groups, no effort to identify factors other than the retrofit that could have affected energy use). These programs were typically the utility's first foray into demand-side management (DSM), involving low-interest financing or utility rebates for a limited set of measures such as attic insulation. In many cases, the retrofitted houses had uninsulated attics; not surprisingly, adding R-19 attic insulation was quite cost-effective. Savings of the space heat fuel ranged from 13 to 21%, with CCEs ranging from \$1.80/MBtu to \$4.40/MBtu, even in relatively mild climates and cases where some attic insulation was already present (see Figure 2). Despite their limitations, these initial evaluations do provide compelling evidence documenting the energy-saving benefits of attic insulation.

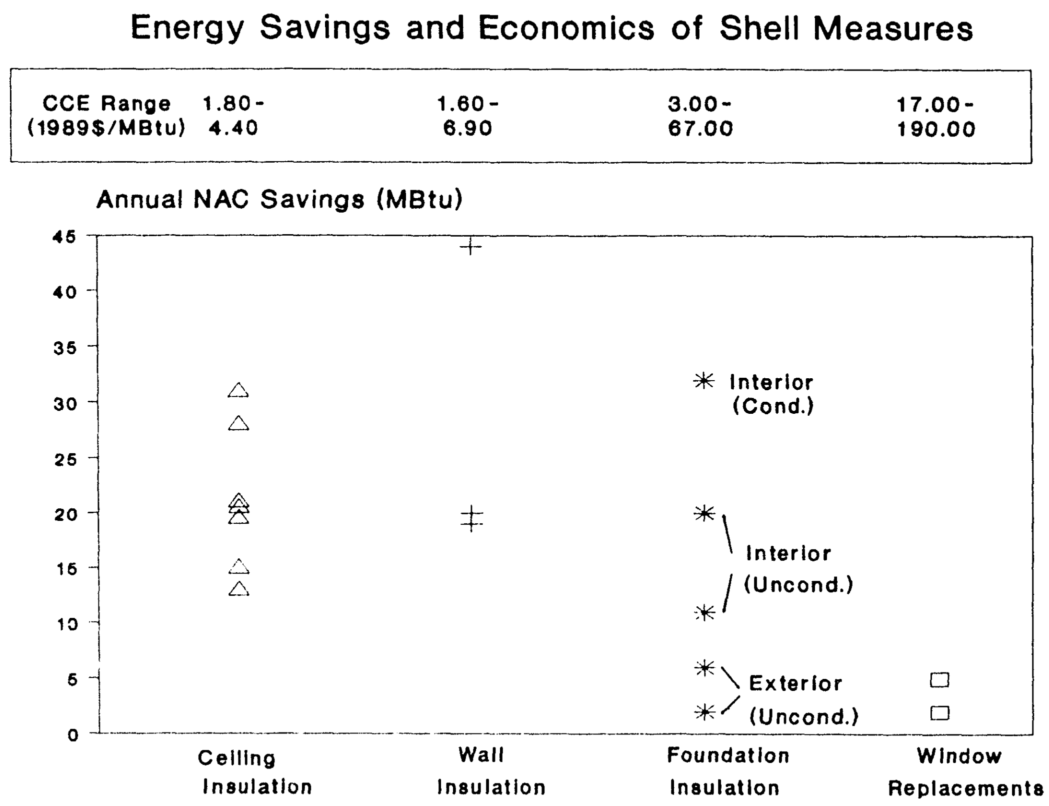


Figure 2. Annual NAC savings and cost of conserved energy (CCE) for individual shell measure retrofits. Average savings from each study are plotted as one data point along with the range in average CCE values for these studies.

Results from several recent retrofit projects have reinforced these initial findings from early utility-sponsored programs. For example, a research study by the University of Illinois found that the normalized annual consumption (NAC) decreased by 17% in five homes after increasing attic insulation from R-14 to R-31 (Hegan et al. 1982). An evaluation of the Cut Home Energy Costs (CHEC) loan program in Manitoba reported annual average space heating savings of 21 MBtu in a group of 47 homes that invested $660/house to increase attic insulation from R-11 to R-40. The average CCE for this group of houses was $2.90/MBtu (McVicar and Carroll 1985). In a sub-sample of 162 homes that participated in a low-income weatherization program sponsored by Ohio utilities in 1987, ceiling insulation reduced the NAC by 12% (Kirksey and Lordo 1989). This study demonstrates that substantial savings can result from ceiling insulation even when initial consumption is relatively low (111 MBtu/year in 6,000 HDD_{65}). We did not analyze the economics of this retrofit because much of the installation work was done by volunteers.

4.3 Wall Insulation

The most common method for insulating walls in existing construction is to blow in high-density cellulose. Data on wall insulation retrofits are drawn from a research study by the Minneapolis Energy Office (Hewett et al. 1986), from a group of houses retrofitted under Wisconsin's Low-Income Weatherization Program (Horowitz et al. 1987), and from the Manitoba CHEC Program (McVicar and Carroll 1985). Compared to attic insulation, wall insulation retrofits involve more complex installation procedures, higher costs, and more uncertainty in predicting savings. This retrofit is labor-intensive because in order to pack each section of a wood-frame wall with insulating material, either the siding is removed or holes are drilled from the interior (and then filled and refinished). Accurate predictions of savings are also more difficult because wall insulation both reduces the conductivity of the wall and reduces infiltration and convective loops within the wall. In addition, changes in the surface temperature of an insulated wall may lead to setting the thermostat for a lower air temperature while maintaining the same level of thermal comfort.

The two U.S. studies that examined wall insulation retrofits were conducted in similar climates (7,500-8,000 HDD_{65}) in homes of similar size (about 1200-1300 ft^2). Average NAC savings (19-20 MBtu) were similar for the two groups (see Figure 2). However, average retrofit costs in the low-income weatherization program were half that of the research study ($800 vs. $1600). Thus, the CCE was much more attractive for homes that participated in the weatherization program compared to the research study ($3.60/MBtu vs. $6.90/MBtu). Data from a recent study by the Wisconsin Energy Conservation Corporation (WECC 1989) indicate that wall insulation costs about $800 in a 1200 ft^2 house based on a survey of Wisconsin CAP agencies and contractors. In the Manitoba study, the average installed cost for wall insulation in 27 homes was about $850/house and consumption decreased by an average of 44 MBtu/year after the retrofit. The average CCE was quite low ($1.60/MBtu), although the climate is more severe than in the U.S. (10,600 HDD_{65}). These data suggest that wall insulation retrofits could be quite cost-effective compared to current fuel costs in severe heating climates when economies of scale can be achieved in large-scale programs or where replacement exterior siding is needed.

4.4 Foundation Insulation

The effects of foundation insulation for *unconditioned basements* were documented in two studies of Minnesota houses. Energy savings were significantly higher in the group of houses in the Minneapolis Energy Office (MEO) study. Savings were 10 and 15% of the NAC, respectively, for interior and exterior insulation (Quaid et al. 1988) compared to the homes monitored by Robinson Technical Services, where savings were 3 and 6% of the NAC (Robinson et al. 1989). CCEs were $5/MBtu and $12/MBtu for the houses in the MEO study, but were much higher for the houses monitored by Robinson. The apparent discrepancy in performance may be due to the fact that the Robinson study focused exclusively on conductive losses and included efforts to reduce basement area infiltration prior to measuring energy use during the pre-retrofit period. Thus, the MEO study included savings from both air sealing and reduced conductive losses, while Robinson measured only the savings from lower conductive losses. In both studies, homes that received interior foundation insulation had larger savings than homes that installed exterior insulation. We excluded the cost of sheetrock when calculating the installed cost of interior foundation insulation because we are primarily interested in the incremental costs that are attributable to the foundation insulation retrofit. In most cases, fire codes mandate sheetrock and thus the total cost to the homeowner would be approximately double that shown in Table 2. However, the extra basement living space is a significant non-energy benefit.

The economics of foundation insulation could also be significantly improved in houses with conditioned basements because the warmer spaces tend to lose more heat. For example, the 24 houses in the Manitoba CHEC program that only installed interior foundation insulation in *conditioned basements* reduced consumption by 32 MBtu/year (McVicar and Carroll 1985). Savings were greater in the Canadian homes compared to the Minnesota homes because of the more severe climate (30% more HDD) and the heated basements. Costs are similar to the Minnesota studies (again sheetrock costs are not included) and the CCE becomes more attractive at $3.00/MBtu.

4.5 Window Replacements

Window replacements tend to be expensive retrofits, while measured data suggest that energy savings are relatively small (see Figure 2). An evaluation of window replacements in 41 homes that participated in Indiana's Energy Conservation Financial Assistance Program (ECFAP) found annual savings of 1.5 MBtu (Hill 1990) at an average cost of $3,350 per house. A group of 41 homes that participated in the Manitoba CHEC program had savings of 5 MBtu/year in a climate with over 10,000 HDD (McVicar and Carroll 1985). Window replacements were the least cost-effective retrofit of all shell options financed by this program. Kinney et al. (1990) report similar results in their evaluation of New York's low-income weatherization program. Their statistical analysis showed that spending a significant portion of program dollars on window replacements were likely to result in low or negative savings. None of these studies reported the pre-retrofit R-value of the windows.

4.6 Warm-Room Experiments

Creating "warm rooms", that is zoning and weatherizing only a portion of a house, can often produce significantly higher savings (about 25% of the NAC) at costs that are comparable to those reported in conventional weatherization programs which typically achieve savings of 10-15%. The warm-room concept was designed especially for elderly, low-income homeowners that incur high fuel expenses to heat large homes. The success of a warm-room retrofit, where heating is limited to those areas most frequently occupied, often depends on the cooperation of the occupant because of significant impacts on amenity level and lifestyle.

The two warm-room studies in the BECA database used different methods to create warm zones. In the Missouri study, selected areas of the house were insulated and received infiltration measures (Wagner and Diamond 1987). The appropriate heating registers were then closed to further the zoning effect. Note that in some cases, closing off registers may lead to inefficient operation of a forced-air system, without adjustments or modifications to the burner and fan (or in extreme cases, without replacement with a smaller furnace). In the Pennsylvania study, attics were insulated and a small, high-efficiency gas heater was installed near the center of the house (McBride 1988). Rooms near the heater were the warm zones. The disadvantage of this method is that there is no heating distribution system and the occupant has less control over temperatures throughout the house. Pipes may freeze in some cold areas, or some rooms may be too warm in order to heat areas further from the heating unit. However, the existing central heating system can be turned on during extreme cold weather. These studies suggest that a warm-room retrofit may be an attractive alternative to conventional weatherization for some elderly residents living in large houses.

4.7 Heating System Retrofits

Measured data are now available on a number of retrofit options designed to improve the efficiency of heating systems. Results are summarized in Figure 3. Energy savings from retrofitting oil furnaces with flame-retention burners have been documented in studies in New York, Michigan and Oregon. This retrofit reduced average oil consumption by 20-32 MBtu/year (14-25% savings) in the three groups at a cost of about $550 (Hoppe et al. 1982; Witte and Kushler 1985; and PECI 1987).[5] The economics of flame-retention burners for oil furnaces are quite attractive, with CCEs ranging from $1.90 to $2.90/MBtu (see Figure 3). Moreover, a recent study conducted by the Alliance to Save Energy (ASE) suggests that savings from this option do not erode rapidly over time based on results from groups of houses located in Wisconsin and Maine (Guyant 1989). Prior to retrofit, steady-state efficiency averaged 68% in the two groups of homes. During the five years following the retrofit, the average efficiency of the oil-fired heating equipment decreased only modestly (from 81% to 77%), even though regular maintenance was not performed on many of the furnaces (e.g., changing air filters).

[5] Percent savings can not directly be compared to retrofits in gas-heat homes because the NAC for oil-heat homes typically includes only space heating, while the NAC for gas-heat homes typically includes space heat, hot water, and cooking.

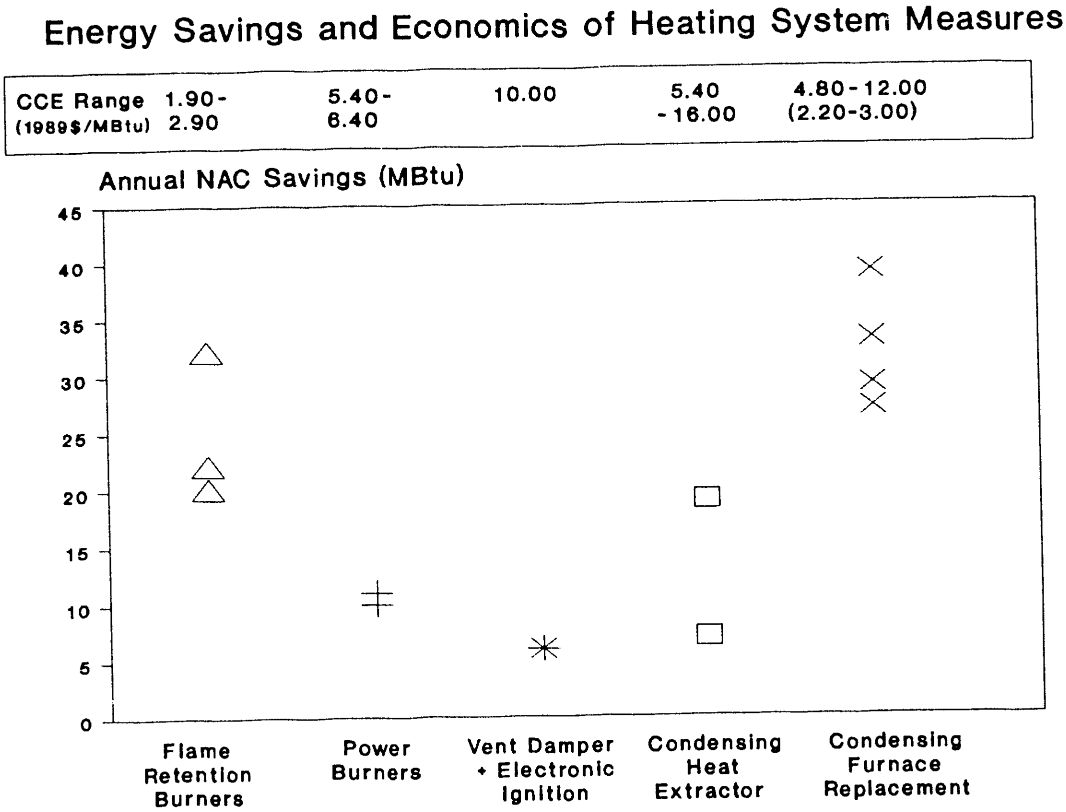


Figure 3. Annual NAC savings and cost of conserved energy (CCE) for heating system retrofits and replacement of condensing furnaces. Average savings from each study are plotted as one data point along with the range in average CCE values for these studies. Flame retention burners were installed in homes with oil-heating equipment while all other retrofits were installed in gas-fired furnaces.

A variety of gas-heating equipment and control options have been tested in R&D projects. Results of these studies suggest that most of the options designed to improve the efficiency of gas-fired equipment have somewhat longer payback times than flame-retention burners for oil-fired systems (see Figure 3). For example, the Alliance to Save Energy (ASE) installed power burners on gas furnaces in Kentucky and Minnesota households, as part of a pilot program. In a power burner, a fan pushes or pulls air through the heat exchanger. With the forced draft, a larger heat exchanger can be used and more heat is removed from the exhaust gases. Oak Ridge National Laboratory (ORNL) evaluated the pilot projects and found that annual gas usage decreased by about 10-11 MBtu (6% of the NAC) in each group (Berry et al. 1987). Retrofit costs averaged $560. Compared to current gas prices, these retrofits are marginally cost-effective, with CCEs of $6.40 and $5.40/MBtu in Kentucky and Minnesota, respectively.

Electronic ignition and vent damper retrofits achieve savings by reducing off-cycle losses. Electronic ignition reduces energy use by eliminating a constantly burning pilot light, while a vent damper shuts when the furnace has cycled off, reducing convective losses up the flue. ASE tested this retrofit combination in Minnesota and found that the average NAC decreased by four percent in 42 houses (Berry et al. 1987). The electronic ignition and vent damper combinations cost $440, giving a CCE of $10.00/MBtu. This retrofit might produce greater savings and improved cost-effectiveness in a milder climate, where the furnace cycles on and off during more of the year. Savings are also a function of how much the furnace is oversized, compared with the heating load. This retrofit might be best applied to an existing system, in conjunction with envelope measures that reduce the heating load.

A condensing heat extractor retrofit appears to offer large potential savings. However, the only measured data are from a study where the hardware was poorly designed. The energy-saving principle behind a condensing heat extractor is to remove the heat of vaporization from the water vapor going up the flue. As part of this R&D project, ASE installed condensing heat extractors on gas furnaces at a cost of $720 each. Gas savings varied significantly, averaging 14% of the NAC in Kentucky but only 4 percent in Minnesota (Berry et al. 1987). Moreover, the electricity use of oversized, 0.25 horsepower fans appeared to offset much of the gas savings.

4.8 High-efficiency Replacement Heating Equipment

Measured data are available from four studies on the costs and savings of replacing heating systems with high-efficiency condensing units (see Figure 3). Two approaches could be used to analyze the economics and energy savings of furnace replacements. The first approach attributes the entire cost and energy savings of the new furnace to higher efficiency and provides an upper bound for cost-effectiveness. This approach implicitly treats the new high-efficiency furnace as a retrofit, which is being installed before the end of the useful life of the existing equipment. The second method assumes that the existing furnace needed replacement, anyway - attributing only the incremental cost and energy savings between a high-efficiency model and a new baseline model to energy conservation. The second method is likely to more accurately reflect installation practices in most programs (i.e., replacement of old heating equipment that is near the end of its useful life) but presents data limitations. Typically, reported data include total installed costs and energy savings relative to the existing furnace. An additional complication is the fact that one of the research studies reported a furnace cost that is a factor of three higher than current prices.

In Table 2, two CCE and simple payback period values are given. The first is calculated using the total installed costs and total savings. The second value in parentheses is calculated by assuming a $500 incremental cost of a condensing furnace over a baseline unit and that 50% of the energy savings are due to the difference between a condensing and a new baseline-efficiency furnace. The incremental savings fraction is based on an assumption that the original unit has an annual fuel utilization efficiency (AFUE) of 60%, the baseline AFUE for a new furnace is 75%, and the condensing furnace has an AFUE of approximately 90%. Currently, the installed cost of a condensing furnace in Wisconsin is about $1500-$1600 (Schlegel 1990).

Two of the furnace replacement studies had very few houses. Condensing furnaces were installed in three Wisconsin houses at an average installed cost of $1880. Average energy use decreased by 27 MBtu/year, although the variance in savings was quite large (42, 9, and 31 MBtu/year respectively). The CCE was $5.90/MBtu using the first method and $3.20/MBtu using the second method. In an earlier study, the Minneapolis Energy Office reported somewhat larger savings in three homes (33 MBtu/year). Average costs were significantly higher ($4750 per house) leading to a CCE of $12.00/MBtu or $2.60/MBtu using incremental savings and costs. Costs for condensing furnaces were unusually high because the product was new on the market at that time.

Sample sizes were larger in the the two other studies. Hill (1990) reported that gas consumption decreased by 29 MBtu/year (19% of the NAC) in 30 homes that received condensing furnace replacements as part of Indiana's Energy Conservation Financial Assistance Program (ECFAP). Installed costs averaged $2,110, which produced a CCE of $6.20/MBtu ($3.00/MBtu using the incremental values). Savings were significantly higher (39 MBtu/year) among a group of 49 houses located in Winnipeg Manitoba with 10,600 HDD_{65}, almost one third more heating degree days than Minnesota (MacInness 1988). The cost of conserved energy was $4.80/MBtu or $2.20/MBtu depending on the analysis method used. In either case, the retrofit is cost-effective.

To summarize, condensing furnace retrofits are marginally cost-effective using a worst-case analysis (CCE between $5-6/MBtu). Using the incremental savings and costs, the CCE ranges from $2-3/MBtu. Thus, condensing furnace replacements are highly cost-effective in cold climates.

4.9 High-efficiency Air Conditioning Replacement Equipment

Measured data on retrofit options designed to reduce cooling energy use are still rare. High-efficiency air conditioners were installed in 12 houses in Austin, Texas to replace existing equipment in an R&D project funded as part of DOE's Retrofit Research program (Hough et al. 1989). Prior to the retrofit, the average Energy Efficiency Ratio (EER) was 6.8 in this group of homes, which increased to 11.4 after installation of high-efficiency equipment, at a cost of about $2760 per house. Household electricity use decreased by 12% after the retrofit, resulting in a CCE of 14¢/kWh. Once again, the economics would be more attractive if the air conditioner needed replacing anyway. In that case, as with heating system replacements, the cost attributed to conservation would be only the incremental cost between a conventional and high-efficiency replacement unit.

4.10 Water Heating Measures

The energy savings and economics of various options designed to reduce water heating usage comes principally from small research studies (Usibelli 1984). A recent study of a subsample of homes that participated in the Hood River Project found that water heating retrofits are highly cost-effective, although the savings for individual measures contain some inconsistencies (Brown et al. 1987). Water heater tank wraps were found to save 972 kWh/year (22% of water heating electricity use) in a sample of 20 homes with submetered water heating energy, yielding a 0.5 year payback. A group of 54 homes that had both water heater wraps and low flow showerheads installed saved 1,001 kWh/year (17% of water heating electricity use), resulting in a CCE of 0.4¢/kWh. Savings can not unambiguously be attributed to these options because water temperatures were also lowered, reducing standby losses in an undetermined number of homes in the two groups.

4.11 House Doctoring

Although more recent monitoring efforts have focused on isolating the effects of individual retrofits, it is often difficult to reliably monitor savings for individual measures. Moreover, some of the most cost-effective program designs involve installing a package of retrofit measures chosen through an on-site energy audit or other analysis. For example, there have been a number of studies documenting the impacts of "house-doctoring" strategies (see Table 3). Typical house-doctoring measures include identification and sealing of convective heat losses using a blower door and infrared scanner, installing double-setback clock thermostats furnace tune-up, and low-cost hot water heating retrofits. House-doctoring is intended to seal obvious air leaks and skim some of the "cream" of easy energy savings through inexpensive retrofits such as water heater wraps.

Table 3. "House-doctoring" retrofit projects.

Label	State	HDD[a] (65°F)	Number of Houses	NAC Pre-Retrofit	Gross Savings		Net Savings[b]		Retrofit Cost (1989$)	SPT	
					Energy	%	Energy	%		(Gross)	(Net)
[Electric Heat]				(kWh)	(kWh)		(kWh)				
E008	WA	4800	5	19,980	1850	9	-	-	730	11	-
E003	CO	6000	23	17,615	2840	16	740	4	1740	7	25
[Gas Heat]				(MBtu)	(MBtu)		(MBtu)				
G058	CO	6000	28	132	13	10	-	-	330	5	-
G027	CA	2900	13	128	16	13	3	2	640	6	50
G070	MN	8000	110	173	14	8	-	-	100	1	-
G071	MN	8000	30	247	21	9	-	-	670	5	-
G005	NJ	4900	12	172	29	17	19	11	490	2	6
G006	NJ	4900	12	99	7	7	7	7	490	10	10
G007	NJ	4900	9	121	27	22	15	12	490	2	4
G008	NJ	4900	9	135	26	19	11	8	490	2	6
G024	NJ	4900	5	164	24	15	13	8	490	3	5
G025	NJ	4900	6	159	21	13	3	2	490	3	24
G026	NY	4900	5	160	24	15	5	3	490	3	13

Notes:

[a] HDD = Heating Degree Days

[b] Net Savings = $(NACpost/NACpre)_{control} * (NACpre)_{treatment} - (NACpost)_{treatment}$

[c] Simple Payback is calculated using first-year energy savings, and local energy prices and retrofit costs (nominal $) at the time of the retrofit.

Princeton's Modular Retrofit Experiment was a research and demonstration project conducted in collaboration with five gas utilities in New Jersey and New York (Dutt et al. 1986). Seven groups of gas-heated homes received house-doctor treatment, with investments averaging $490 per home (see Label G005-G008 and G024-G026 in Table 3). After adjusting for changes in consumption in the control group, the NAC decreased by about 8% in the entire sample of 58 houses. There were significant differences in savings and thus payback times among the houses in each location, which the authors attributed in part to differences in physical characteristics and technical opportunities in each set of houses as well as limited and apparently uneven training received by utility staff that implemented the house-doctoring retrofits.

Average energy savings were also strongly correlated with initial consumption levels in the Princeton Modular Retrofit Experiment (MRE). Before the retrofit, average gas consumption ranged from 121 to 172 MBtu/year in six of the seven groups of houses, extremely high values for a 4,900 HDD climate (Labels G005-8, G024-26). Energy savings (gross) were 21 to 29 MBtu/year for these homes and the simple payback times were two to three years (see Table 3). In contrast, average gas usage decreased by only seven MBtu in the group of homes (Label G006) that used much less energy prior to retrofit (99 MBtu/year). Not surprisingly, the economics were not nearly as attractive for this group of homes (SPT of 10 years).

There have been a number of variants in the original house-doctor approach tested by Princeton researchers in New Jersey. During the same period, LBL researchers evaluated house-doctoring, with retrofit options adapted to a group of Northern California homes (O'Regan et al. 1982). They concluded that cost-effectiveness could be improved at mild-climate sites by focusing on homes with either high infiltration rates or those that could be retrofitted with low-cost, non-infiltration measures such as intermittent ignition devices and water heater tank and pipe wraps. The Minneapolis Energy Office (MEO) experimented with the "low end" of house-doctoring in 110 houses (Brummitt 1984). Homeowners performed the work themselves after attending training sessions. Blower doors or infrared scanners were not used, and only $100 was spent per house (see Label G070). Initially, annual gas consumption was 173 MBtu in the 110 homes and decreased by 14 MBtu after the retrofit (8% NAC savings), resulting in a simple payback period of only one year. MEO also tested house-doctoring in a group of 30 homes with extremely high energy-usage (Quaid and Faber 1988). In these homes, pre-retrofit consumption averaged 247 MBtu/year. Savings of 21 MBtu (9% of the NAC) were achieved at a cost of $670, yielding a 5-year payback (Label G071). Sun Power Consumer Association tested a minor variant of house-doctoring, called the "house-nurse" approach, in a group of 28 Colorado houses (Proctor and deKieffer 1988). NAC savings of 10% were achieved for an average cost of $330, yielding a 5-year payback.

Based on these field tests, house-doctoring has been shown to be a cost-effective retrofit strategy (i.e., SPT less than five years) in both mild and severe heating climates, particularly if retrofit costs can be contained and the retrofit is targeted to homes with high infiltration rates or high energy users. Thorough training of installation contractors coupled with adaptation of retrofit options to the local building stock also appear to be key ingredients to success.

5. DOE WEATHERIZATION ASSISTANCE PROGRAM: NATIONAL AND STATE EVALUATIONS

In this chapter, we discuss the evolution of DOE's Weatherization Assistance Program based on state and national evaluations of program impacts. We attempt to build on previous studies by Schlegel, McBride, and Thomas (1990) that provided a comprehensive assessment of the state-of-the-art in low-income weatherization and identified key policy, program, and technical issues as well as Schlegel and Pigg (1990) which examined the potential for cost-effective low-income programs based on recent evaluations from the Midwestern United States. We present a more detailed discussion of measured data on energy savings, costs, and economics of the low-income weatherization program. Our objectives are to analyze program performance trends over time, document innovative program strategies, and examine results from sectors that are difficult to reach effectively (e.g., manufactured housing).

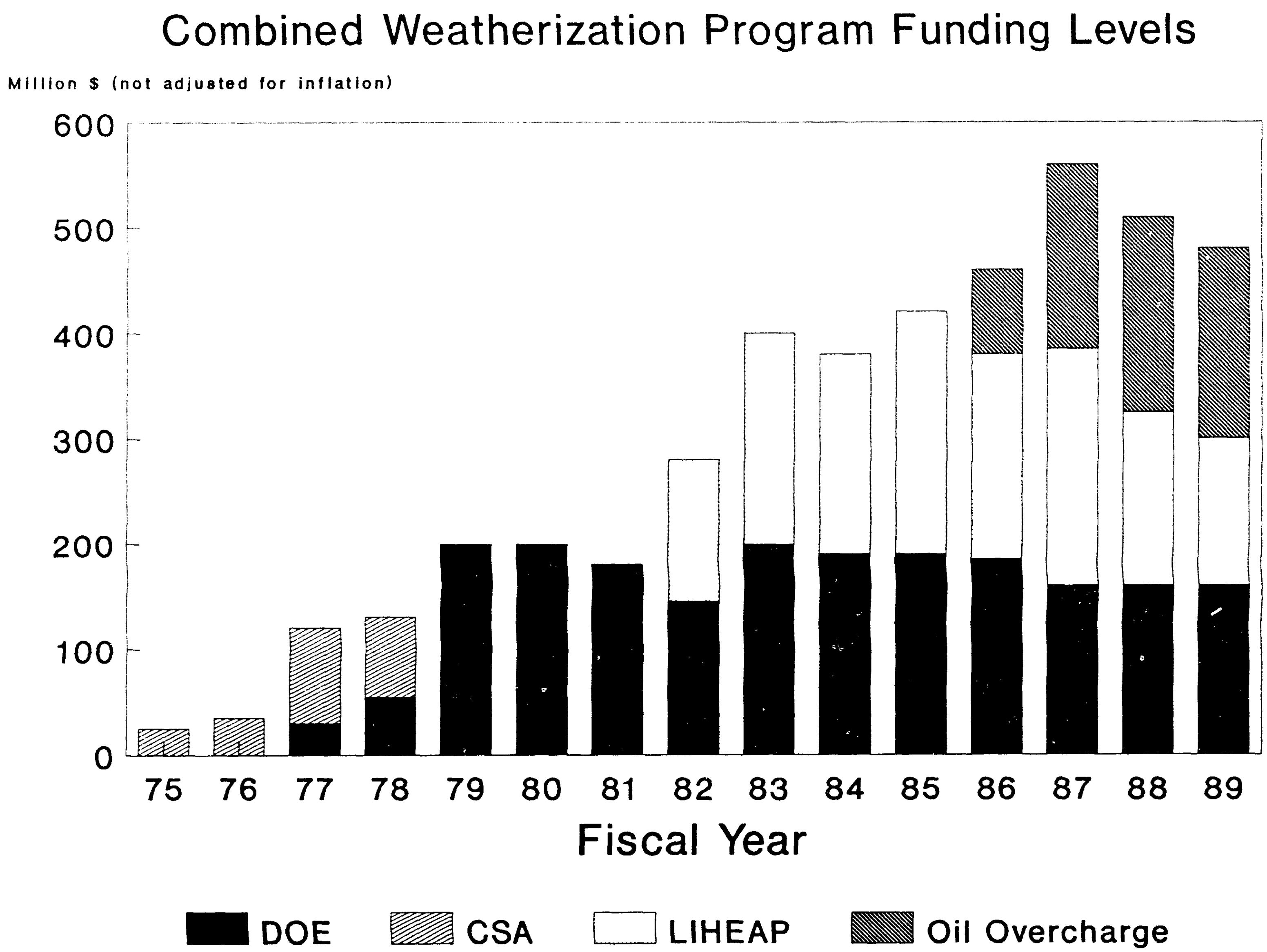
5.1 Background

The U.S. Department of Energy (DOE), in conjunction with state and local agencies, has implemented the Weatherization Assistance Program (WAP) targeted at low-income households since the late 1970s.[6] The program is implemented at the local level principally by Community Action Agencies (CAA). Direct appropriations for DOE's WAP program have been slowly declining since 1983, ranging between $160-200 million annually (Schlegel, McBride, and Thomas 1990). However, overall funding for low-income weatherization increased (in nominal dollars) until 1987 due principally to funding from the Low-Income Home Energy Assistance Program (LIHEAP) and oil overcharge restitution funds (see Figure 4).

Nationally, only about 18% (four million homes) of the eligible low-income houses have been weatherized (Beschen 1990). About 265-300,000 homes are being weatherized annually. At present levels of funding, Schlegel, McBride, and Thomas (1990) estimated that it will require 60 years to weatherize the currently eligible homes.

In a dozen states, one third to one half of all the eligible homes have been weatherized (Beschen 1990). Typically, these are northern states with low population densities. Even in those states that have been among the most aggressive in implementing the DOE program, many homes remain to be weatherized. For example, it is estimated that about one-fourth of the eligible low income homes have been weatherized in Michigan (Witte 1990).

[6] During the 1970s, low-income weatherization programs were funded by both DOE and the Community Services Administration (CSA), successor to Office of Economic Opportunity. CSA was eliminated in 1981.



Source: Schlegel, et al., 1990

Figure 4. Annual funding levels for low-income weatherization from various federal sources including Department of Energy (DOE), Community Services Administration (CSA), Low-Income Home Energy Assistance Program (LIHEAP) and oil overcharge restitution funds. Source: Schegel et al 1990.

5.2. Energy Savings and Cost-Effectiveness

Until recently, efforts to evaluate and measure actual impacts of low-income weatherization (LIW) have been sporadic. With one or two exceptions, primary responsibility for program evaluation has fallen to the states, even though WAP is a national program. DOE did sponsor a somewhat limited national evaluation conducted by the Energy Information Administration (EIA), which was based on energy consumption data from households weatherized in 1981. Recently, DOE has asked Oak Ridge National Laboratory to design and conduct a national evaluation to assess weatherization program impacts; five separate studies will be conducted during 1991-1993 (Beschen and Brown 1990). A few states have conducted thorough and comprehensive local evaluations, but most states have not been systematic in monitoring actual results and using this information to improve their programs.

One trend is clearly evident from a review of weatherization evaluation studies: the quality of data and analysis have steadily improved over time. For example, early program evaluations (before 1980) typically collected only annual energy consumption, used crude weather normalization techniques, documented only materials costs, did not include control groups, and often did not collect information on basic building characteristics (e.g., conditioned area). Program evaluations conducted during the 1980s increasingly used PRISM to analyze and weather-normalize utility billing data, often included control groups, and collected more detailed data on building and equipment characteristics and operation in order to help explain variance in program results.

5.2.1 Program Evaluations conducted before 1980

The top section of Table 4 includes results from a number of pre-1980 state evaluations of the LIW program: Missouri, Indiana, Minnesota, Pennsylvania, Kentucky, and Vermont.[7] Virtually all homes in these studies received ceiling insulation and caulking and weatherstripping, while some homes also installed wall insulation and storm windows. With the exception of Minnesota, pre-retrofit energy consumption was generally quite high, (143-236 MBtu/year) considering the severity of the climates in these states. Annual energy savings ranged from 16-52 MBtu (11-23% of the NAC), although savings tended to be lower in the Minnesota studies (7-10% NAC savings). It is likely that the relatively low initial consumption levels partially explain the lower savings in Minnesota homes. Estimated contractor costs for the retrofits varied from $400 to $2,500 per house. The cost of conserved energy (CCE) values ranged from $1.70 to $5.60/MBtu, with the notable exception of the Minnesota studies where CCE values were significantly higher ($15-23/MBtu). However, limited conclusions can be drawn from this entire group of studies because, overall, data quality is relatively poor.

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[7] LBL reviewed evaluations from about half a dozen other states which were conducted during this period, but data quality or methods did not meet the minimum threshold criteria for inclusion in the BECA-B database.

Table 4. Federal/state low-income weatherization programs.

Label	Year State	HDD (65° F)	No. of Houses	Retrofit Measures	Normalized Annual Consumption: Pre-Retro (MBtu)	Normalized Annual Consumption: Average Savings (MBtu)	Normalized Annual Consumption: Average Savings (%)	Space Heating Intensity: Before (Btu/ft^2-HDD_{65})	Space Heating Intensity: After (Btu/ft^2-HDD_{65})	Retro. Cost (89$)	Simple Payback (Years)	CCE ($/MBtu)
Early Program Evaluations												
G021.1	1977 MO	5160	21	IX,CW	175	20	11			760	13	4.10
G021.2	1977 MO	5160	45	IX,CW	236	44	19			950	8	2.40
G021.3	1978 MO	5230	44	IX,CW	231	52	23			2530	16	5.40
G023	1978 IN	5580	30	IA,IF,CW,HS,WH	220	46	21	29.6	22.1	2380	14	5.60
M010.1	1978 MN	8310	59	IA,CW,DR,WR,WM,IW	139	14	10	16.6	14.9	1570	13	15.20
M010.3	1978 MN	8310	19	IA,CW,DR,WR,WM,IW	130	9	7	16.1	15.0	1470	21	23.40
G019	1979 PA	6280	30	IA,CW,WM	207	29	14			1260	8	4.80
G022	1979 KY	4730	138	IA,WM,DR,CW	143	16	11			410	5	2.80
O006	1980 VT	7880	13	IA,WM,DR						2200	4	5.60
Post-1980 Program Evaluations												
M026	1981 NATIONAL		965	IA,IW,IP,WM,CW,DR	133	14	10			1380	13	11.00
G001	1981 WI	7600	11	CW,IA,WH,IS	144	21	14	17.6	14.6	2220	16	11.70
G065.1	1981 MN	8010	239	CW,IA,WH,DR,WM,IP,IW	161	23	14	19.2	16.4	1110	7	5.30
G057.1	1982 WI	7640	243	CW,IA,WM,IS,DR,IP,ID	124*	13	10	12.5[1]	11.2	1560	18	13.30
G076.1	1983 MI	6720	364	CW,IA,WM	182	21	12	24.2	20.7	1090	7	5.70
G073.1	1984 MN	8000	155	CW,IA,WM,IW,IP	128*	12	9	14.0[1]	12.7	1250	17	9.90
G085	1984 IL	6100	497	CW,IA,WM,T,IW,IP	188[4]	14	8			890	10	6.70
G077.1	1984 MI	6720	155	CW,WM,IA	177	17	10	22.4	19.7	1060	9	6.90
G056.1	1985 OH	6000	1083	WH,CW,IS,ID,IA	153*	18	11	15.7[2]	13.4	2000	18	13.00
G075.2	1986 MI	6720	65	CW,WH,WM,IA,IS	172	23	13	16.3	14.2	1070	10	6.50
G080	1988 NY	7000	683	PI,WH,IA,IW	156*	19	12	13.1[2]	11.4	990	9	5.60
G083	1988 IL	6090	192	PI,RD,IA,WR,IW,IF,WM,IS	179[4]	21	12	14.1	11.8	1030	10	5.40
G084	1988 VA	4300	91	CW,IA,WM,RD,WH,WR	104*	7	7	19.6[3]	17.3	1010	26	16.10
Demonstration Programs												
M008.2	1979 CSA/NBS Shell/Sys.	6470	73	IA,IW,CW,WM,HS,WH		62	-	18.6	10.9	2920	6	5.20
M008.3	1979 CSA/NBS Shell Only	5050	69	IA,IW,CW,WM,WH		23	-	20.1	16.5	2000	11	9.70
G075.1	1986 MI	6700	173	CW,IW,IA,WH,WM,T	172	31	18	16.3	13.2	1020	7	3.60
G062	1988 MN M200	8000	128	IA,IW,IS,CW,T,IP	142*	25	18	10.5[1]	8.2	1330	11	5.90
M029.1	1989 VA Pilot	4300	43	PI,WH,IA,IW,SD,RD,HS	153[5]	24	16	21.0	15.7	980[6]	6	4.50
Pilot Programs Targetting High Users												
G071.1	85 MN Project Choice	8010	30	PI	247*	21	9	15.5[1]	14.1	670	5	4.50
G071.2	85 MN Project Choice	8010	13	PI,IA,IW	229*	48	21	14.3[1]	11.3	2510	9	5.70
G074.1	1984 MI HRW	6560	41	CW,WH,IW,IA,HR,HS	388	95	25	30.7	21.9	4040	6	4.00
G074.2	1985 MI HRW	6560	158	CW,WH,IW,HS,IA,HR	376	81	21	32.2	24.8	3850	7	4.50

Key for Table 4

Label: Letter refers to fuel used as main space heating fuel (G = Gas, M = Mixed fuel, O = Oil). Summaries of studies are arranged by label in Volume II of this report.

Retrofit Measures: (Only listed if they were installed in 20% or more of the sample.)

IA	Attic insulation	IF	Subfloor insulation
IW	Wall insulation	CW	Caulking/weatherstripping
IP	Foundation insulation	PI	Pressurization, infil. reduction
IS	Sill box insulation	IX	Misc. shell insulation
ID	Duct insulation	DR	Storm doors
HS	Heating system retrofit	WH	Water-heating retrofit
WM	Storm windows	RD	Replace doors

Normalized Annual Consumption (NAC) pre = Weather-normalized annual consumption of space heat fuel prior to retrofit. Projects that use PRISM in energy analysis are indicated by *.

Retrofit Cost: The listed retrofit costs include materials and labor, but not program overhead. See Appendix E for a discussion of overhead costs.

CCE = Cost of conserved energy (calculated with a 7% discount rate).

Footnote 1 - Based on the Residential Energy Consumption Survey (EIA 1989), LBL estimated the space heating energy use fraction of the normalized annual consumption (NAC) for different climate regions when no enduse breakdown of the data was given by the study authors. In climates with 5,500-7,000 HDD_{65}, LBL assumed that space heating accounts for 75% of total gas use.

Footnote 2 - In climates with more than 7,000 HDD_{65}, LBL assumed that space heating accounts for 80% of total gas use.

Footnote 3 - In climates with 4,000- 5,5000 HDD_{65}, LBL assumed that space heating accounts for 70% of total gas use.

Footnote 4 - LBL estimated the NAC from space heating consumption by assuming that space heating accounts for 75% of total gas use.

Footnote 5 - LBL estimated the NAC from space heating consumption by assuming that space heating accounts for 70% of total gas use.

Footnote 6 - LBL estimated the program cost (labor and materials cost) from the total cost (program plus administrative costs) by assuming that one third of the total program cost was administrative costs. (See Appendix E of Volume II for data on administrative costs).

5.2.2 1979 CSA/NBS Optimal Weatherization Demonstration

Lower than expected savings from the field (e.g., 10% actual vs. 20% expected) prompted the Community Services Administration to enlist the expertise of the National Bureau of Standards (NBS) in 1979. NBS designed and conducted a 12-city optimal weatherization demonstration to improve the energy savings and cost-effectiveness of standard weatherization procedures. Retrofit options were expanded beyond the traditional measures of caulking and weatherstripping, attic insulation, and storm doors and windows to include more extensive improvements to the thermal envelope as well as various space heating system or domestic hot water system options. Space heating energy consumption decreased by 31% overall in the 142 houses (Crenshaw and Clark 1982). A major finding of the study was that inclusion of heating and hot water system retrofits were essential to improved program performance. Average space heating energy use decreased by 43% in the 73 homes that received heating and hot water system retrofits in addition to building shell measures, compared to a 21% reduction in the 69 homes that installed only shell measures (see Figure 5). The combination of heating system and shell retrofits were roughly two times more cost-effective than shell measures alone (CCE of \$5.80/MBtu vs. \$10.80/MBtu) for homes in the CSA/NBS Demonstration project.

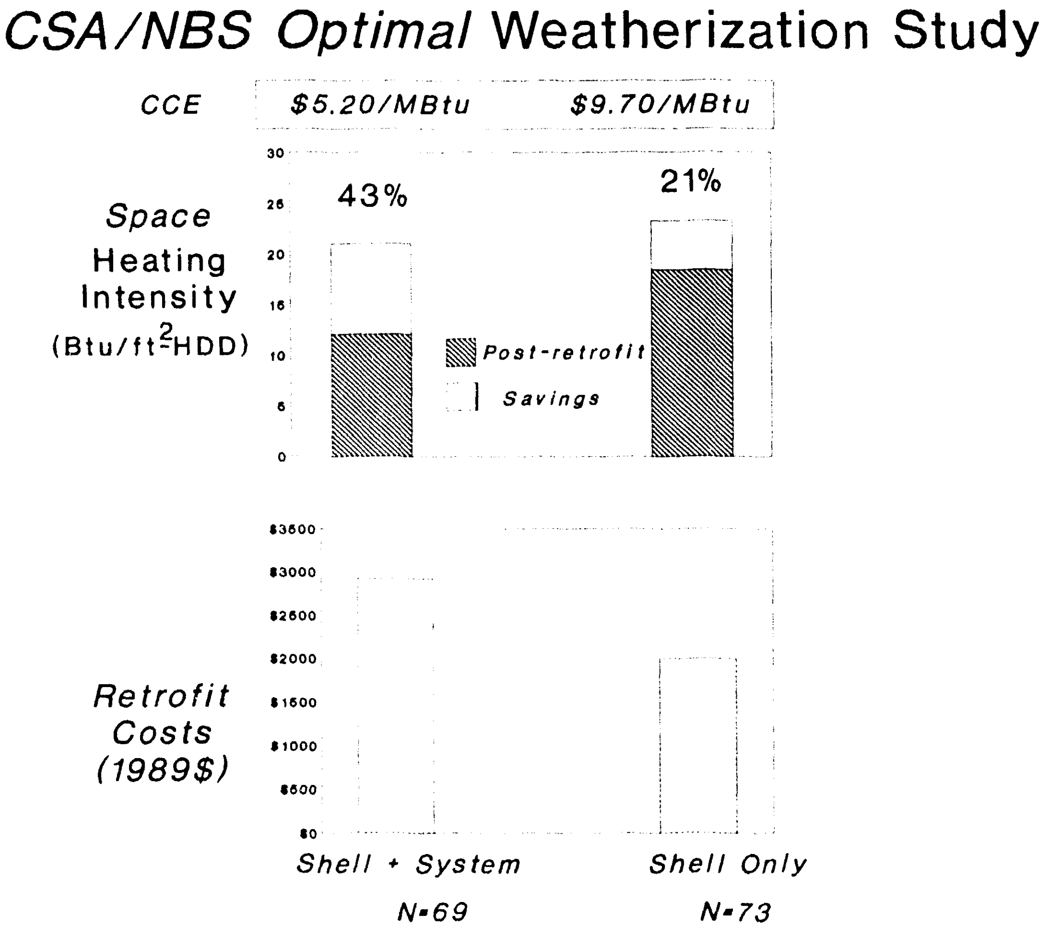

Figure 5. Comparison of space heating intensities, retrofit costs (in 1989$) and cost of conserved energy (CCE) for two groups of homes that participated in the 12-city 1979 CSA/NBS Optimal Weatherization study: 73 homes that installed both envelope and heating and hot water system measures versus 69 homes that received only shell measures.

The positive results from various demonstration projects (e.g., the CSA/NBS optimal weatherization study, Brookhaven National Laboratory's field tests of retrofits for oil-fired heating equipment) prompted other groups such as the Alliance to Save Energy and several state weatherization programs (e.g., Michigan) to conduct pilot programs. These demonstrations typically tested the effectiveness of major heating system retrofits and the potential for incorporating them with traditional weatherization, which had been limited to shell measures.[8] These pilot programs were part of a broader trend by some states to install a wider range of cost-effective retrofit measures. Other examples include increased saturation of wall insulation in Michigan, Minnesota, and Ohio, and installation of condensing furnaces in Wisconsin.

5.2.3 1981 National Evaluation of Weatherization Assistance Program

The first national study of WAP was conducted by the Energy Information Administration (EIA), which analyzed 965 randomly selected homes that were weatherized under the 1981 DOE program (Peabody 1984). The EIA study had some serious methodological and data quality problems, but it did provide a national assessment of program impacts based on metered energy use.[9] About 65% of these homes heated with gas, 21% used fuel oil or kerosene, while 5% relied on electric heat. The EIA study provides a snapshot of the type of retrofit measures being installed in the early years of the program and their relative saturation in the study sample: weatherstripping or caulking (91%), attic, wall or floor insulation (81%), storm windows or doors (53%), and other services (69%). EIA found that total energy consumption of the main space heat fuel (NAC) decreased by about 10% after weatherization (see Table 4, Label M026). Based on materials costs, LBL estimated that the contractor costs of these retrofits would be about $1380 per house (in $1989), which would give a CCE of $11/MBtu.

5.2.4 State Program Evaluations Conducted Since 1980

The middle section of Table 4 summarizes results from states that conducted comprehensive evaluations of the standard low-income weatherization program since 1980: Wisconsin, Michigan, Minnesota, Ohio, New York, Illinois, and Virginia (Fulmer 1982; McKenzie and Pheneger 1983; Hewitt et al. 1984; Kushler and Witte 1985; Carmody 1986; Patterson and Mystikides 1987; Kushler and Witte 1986; Gregory 1987; Kushler and Witte 1988; Kinney et al. 1990; Haber and Hastings 1989; Randolph et al. 1991). Aside from Virginia, all the evaluations are clustered in six northern states (see Figure 6). In the northern states, total energy use of the space heat fuel (NAC) decreased by 9-14% in the 11 studies, while absolute savings ranged from 9-23 MBtu/year. In aggregate, these evaluations provide a well-documented assessment of the savings achieved by the more "advanced" low-income weatherization programs (as of the early to mid-1980s) in cold climate states (>6000 HDD). CCEs ranged between $5.30-$13.30/MBtu, although CCEs tend to be clustered at the low end of this range ($5-9/MBtu) in the more recent evaluations, with the exception of the 1985 Ohio study (see Figure 7). Compared to the other

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[8] These studies are discussed in detail in Chapter 4 in the section on heating system retrofits.

[9] For example, the study did not include a control group or any on-site audits or diagnostics and reported only materials costs. Moreover, it was unclear how fuel consumption data were weather normalized or how the percentage of the main fuel used for space heating was calculated.

programs, Ohio did not emphasize insulation measures. Analysis of homes in the Ohio program found that the subset that installed more insulation was much more cost-effective than the overall program average (Gregory 1987).

Post-1980 State Low-Income Weatherization Evaluations in BECA Database

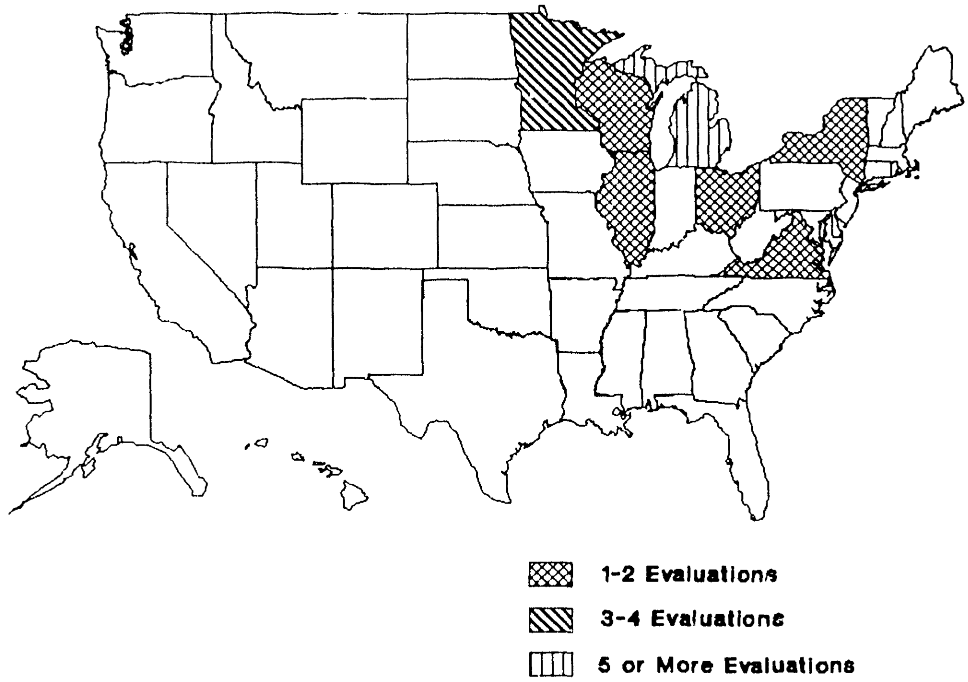

Figure 6. Geographic distribution of state evaluations of the DOE low-income weatherization program conducted since 1980 that are included in the BECA database. Several other states (e.g., Pennsylvania) are currently conducting program evaluations which are not yet completed and we excluded some state evaluations because they did not meet the minimum data quality requirements for BECA.

The 1988 Virginia evaluation is the only recent evaluation of a weatherization program in a relatively mild climate. Measures installed include intensive caulking and weatherstripping, attic insulation, storm windows, and replacement windows. The program achieved average NAC savings of only seven MBtu/year (7%) and the CCE was over $16/MBtu (Randolph et al. 1991). Absolute savings in these Virginia homes were significantly lower than those reported for houses in cold climate states. Retrofit costs were comparable, and thus CCEs were much higher in the Virginia program (see Figure 7). The measures installed in Virginia appear to be typical of current practice in many states with mild climates. Thus, the results from Virginia provide one benchmark which can be used to estimate performance in mild climate states that have not conducted evaluations.

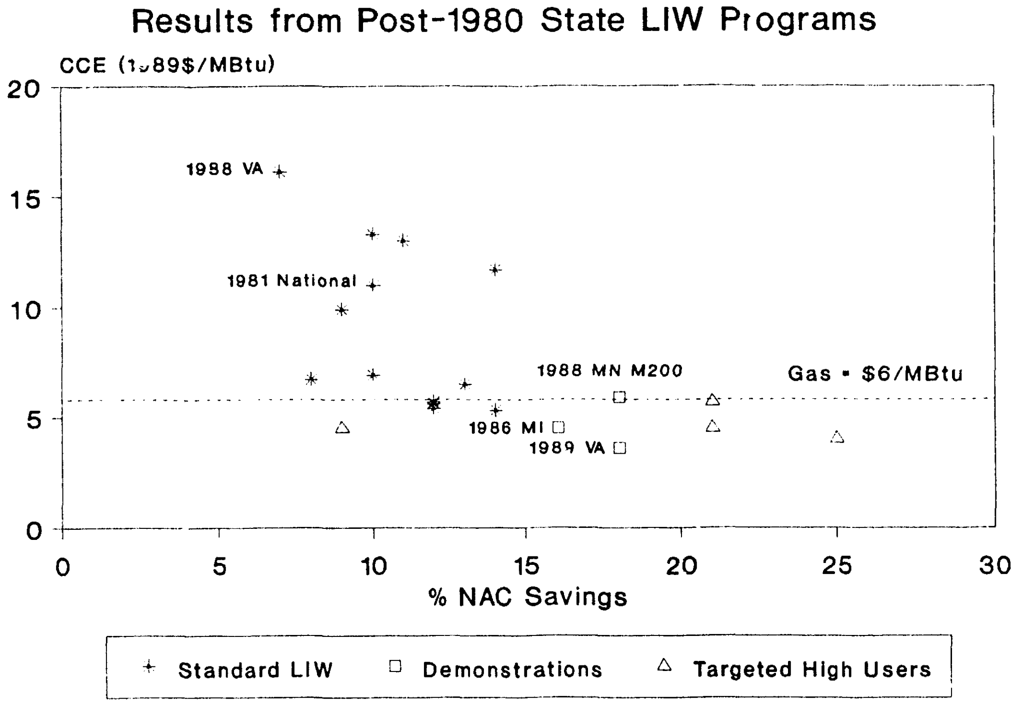

Figure 7. For the post-1980 state weatherization evaluations shown in Table 4, the average cost of conserved energy (CCE) is plotted against percentage savings of the space heat fuel (NAC or normalized annual consumption). The 20 data points represent results from over 4500 homes (The CSA/NBS demonstration is excluded since we do not have NAC data.) The dashed line represents the average U.S. residential price for natural gas. The most successful programs are below the dotted line and on the right side of the graph indicating that they are cost-effective compared to current fuel prices and also produced significant fuel savings.

Finally, it is worth noting that the process and results of these program evaluation efforts have led to significant improvements in the delivery and performance of the low-income weatherization program in these and other states with similar climates. The lack of measured data from states with mild climates is a serious gap in our ability to assess low-income weatherization performance, one which the current evaluation being conducted by ORNL for DOE will need to address.

Space heating energy use (and the savings potential) are strongly affected by the severity of the climate and house size. One way to capture and account for these factors across programs is to calculate space heating intensities before and after weatherization (see Figure 8). We define the space heating intensity index as heating energy consumption (in Btus) per square foot of heated floor area per heating degree day (base 65^{o}F). One limitation of this index is that heating energy consumption is rarely metered directly. Often only NAC values were reported. In these cases, LBL calculated heating energy use by applying the space heating fractions estimated by EIA for gas-heated homes in similar climates based on the 1989 RECS survey.[10] It was not

[10] Based on statistical analysis, EIA estimated that space heating accounted for about 80% of total gas use in regions with more than 7000 HDD and about 75% in regions between 5500-7000 HDD.

possible to use the space heating values from PRISM directly because they were not reported in all studies. Moreover, a number of studies have found that the space heat term in PRISM tends to overestimate actual space heat usage. In other cases, annual heating energy was derived by subtracting estimated baseload usage based on summer gas consumption. As Figure 8 illustrates, low-income homes weatherized in Michigan in 1983 and 1984 appear to use significantly more heating energy than homes in the six other states, both before and after retrofit, even after adjusting for house size and climate severity. After weatherization, the space heat intensity of Michigan homes is 14-21 Btu/ft^2-HDD compared to 11-15 Btu/ft^2-HDD for low-income homes in the other states. One encouraging trend is that space heating intensities after retrofit in some states (e.g., Minnesota, New York) are approaching the overall U.S. stock average for existing gas-heated single-family houses (9.6 Btu/ft^2-HDD) and are lower than the RECS estimate of 13.6 Btu/ft^2-HDD for the U.S. low-income housing stock (see Figure 8). Historically, heating energy usage in low-income homes have significantly exceeded stock averages as is shown in Figure 8. While space heating intensity is a useful figure of merit, these results should be interpreted with caution given data limitations, inconsistencies, and other uncertainties.

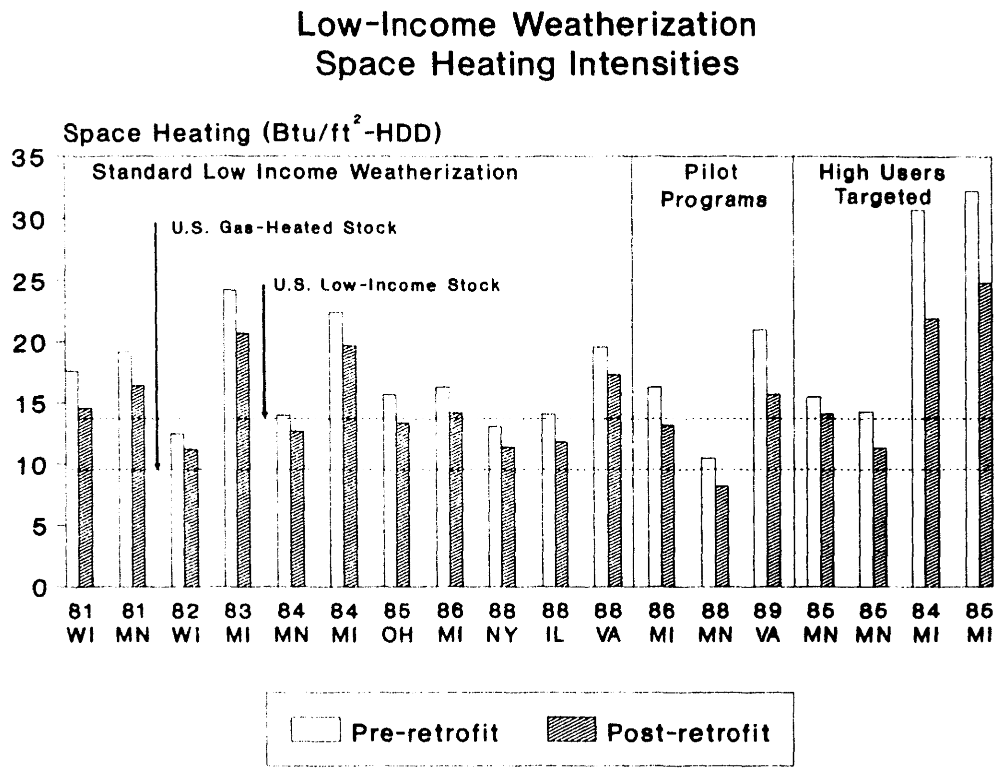

Figure 8. Pre- and post-retrofit average space heating intensities from post-1980 evaluations of state low-income weatherization programs, demonstration projects of optimal weatherization techniques, and low-income programs that targeted high energy users. (The programs shown here are the same as in Table 3.) In cases where no enduse breakdown of the NAC was given, space heating energy was calculated by applying Energy Information Administration (EIA) estimates of space heat fraction of total gas use in various climates to the NAC value derived from PRISM or by subtracting estimated baseload consumption. Space heating energy use was then normalized by average conditioned floor area and normal year heating degree-days for each site (base 65°F). For comparison, we show an EIA estimate of space heating intensities for U.S. gas-heated stock and low-income stock (125% of poverty line) based on the 1987 RECS survey (EIA 1989a).

5.2.5. Minnesota, Michigan, and Virginia Demonstration Programs

Results from three recent weatherization demonstration projects are particularly encouraging and offer well-documented approaches for significant improvements in energy savings and cost-effectiveness in both cold and milder climates. The 1988 Minnesota M200 project and the 1986 Michigan low-income weatherization pilot offer insights into optimal retrofit strategies to pursue in more severe heating climates. The 1989 Virginia weatherization pilot suggests that large savings and cost-effectiveness can also be achieved in milder climates (4,300 HDD_{65} in this case).

The M200 program was designed by the Underground Space Center at the University of Minnesota to increase the cost-effectiveness of low-income weatherization programs in Minnesota (Shen et al. 1990). Two hundred homes were randomly selected and weatherized in 1988; 128 homes were included in the final analysis. Almost all of the homes used gas for space heating (97%). The optimal weatherization approach included the following procedures:

1) An energy auditor visits the home and conducts client education, inspects the heating unit and heat distribution system, determines how much insulation and what repair materials the weatherization crew will need, and conducts a blower door test.

2) If specified by the energy auditor, the heating contractor is called in to deal with safety problems or furnace efficiency improvements.

3) If specified, the weatherization crew installs materials and conducts repairs (if called for) in the following order. Uninsulated walls are brought up to R-11 by installing high density (3.5-4.0 lb/ft^3) cellulose by removing the siding and using a tube feed method. Next, attic bypasses are sealed and attic insulation is installed. Houses with less than R-11 ceiling insulation were brought up to R-44. Large duct leaks are then sealed. A blower door reading is taken to determine whether further air sealing is cost-effective and safe. The cost-effectiveness criteria requires that each 100 cfm air reduction cost less than $40 and the minimum air exchange is 1200 cfm at 50 Pascals.

4) Houses with forced air distribution systems are pressure balanced. Additional measures recommended by the energy auditor are then installed.

5) Finally, a blower door test and, if possible an IR scan, are done to check the success of the retrofitting. Safety checks are also performed to insure that no possible health or safety problems remain after the completion of the work.

Figure 9 compares the saturation of measures in the 1988 M200 demonstration program and the 1984 Minnesota state low-income weatherization program (Carmody 1986).

The saturation of high-density cellulose wall insulation, blower-door guided sealing of bypasses, heating system work, and clock thermostats were all increased in the M200 program compared to the previous state weatherization evaluation in 1984. Storm windows were dropped from the protocol for the M200 program and caulking and weatherstripping was dramatically reduced.

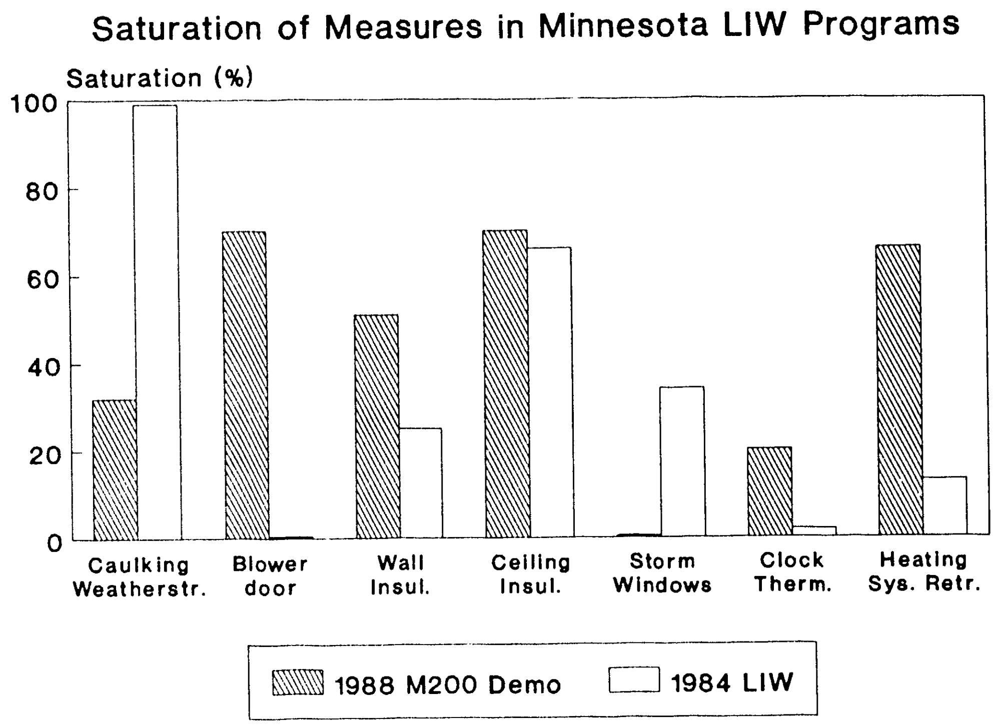

Figure 9. Saturation of measures in the 1984 Minnesota low-income weatherization program (Carmody 1986) and the 1988 M200 demonstration program (Shen et al. 1990).

For the M200 program, average NAC consumption in the 128 houses decreased from 142 MBtu/year before the retrofit to 117 MBtu/year (18% savings). The cost per house averaged \$1330 (\$840 for labor and \$490 for materials), yielding a CCE of \$5.90/MBtu. Gas savings and overall economics in the M200 program are markedly improved over the previous measured results in the Minnesota low-income program: energy savings almost doubled, while the CCE decreased from \$10 to \$6/MBtu (Label G062 and G073.1 in Table 4). Moreover, these results are particularly impressive because the M200 homes had a low consumption base; average pre-retrofit space heating intensity was already lower than the post-retrofit space heating intensities reported in other weatherization evaluations.

In 1986, Michigan experimented with a new priorities list of installed measures in an attempt to increase the cost-effectiveness of its existing weatherization program (Kushler and Witte 1988). Figure 10 shows the relative saturation of measures in the two groups of houses. The new priority measures list placed increased emphasis on wall insulation, low flow shower-heads, and clock thermostats and less emphasis on the use of storm windows compared to the existing program. Additionally, the new program decreased the required ceiling insulation level from R-38 to R-19. The lower saturation of water heater wraps in the new program was due to eligibility not program design.[11]

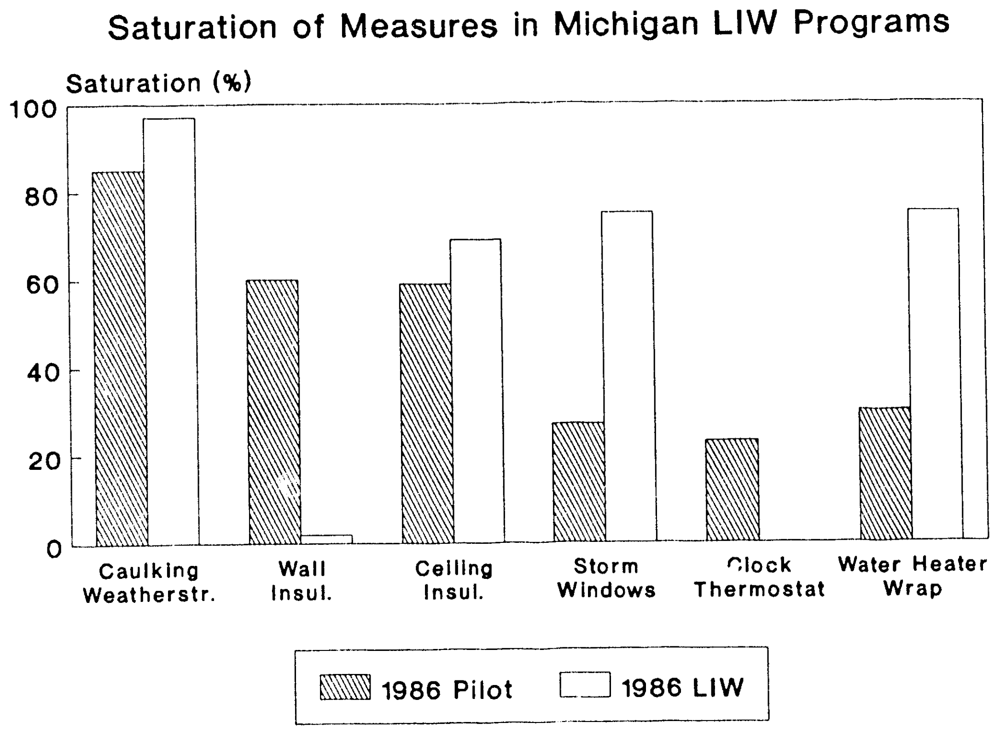

Figure 10. Saturation of measures in the 1986 Michigan low-income weatherization program and pilot (Kushler and Witte 1988).

Average expenditures per house were similar: $1070 for the standard program versus $1020 for the pilot program. The NAC decreased by an average of 31 MBtu/yr (18%) in the pilot program homes, while savings were 23 MBtu/yr (13%) among homes that used the existing procedure (see Label G075.1 and G075.2 in Table 4). The average CCE for homes that were retrofitted based on the new measure priority list was $3.60/MBtu compared to $6.50/MBtu for homes that used the existing approach.

The Virginia Center for Coal and Energy Research evaluated Virginia's 1988 weatherization program and then designed and tested a protocol to increase savings and cost-effectiveness (Randolph et al. 1991). Weatherization crews received a two-week training course to learn the new installation techniques. The results from using the new protocol show the dramatic improvements that can result when a traditional weatherization program is updated with the latest techniques and measures. The existing program emphasized intensive caulking and weatherstripping concentrated in the neutral pressure plane (over 75% of the houses received more than 20 tubes of caulking compound), attic insulation, replacement windows and storm windows (see Figure 11). The original program achieved NAC savings of seven MBtu/year (7%) and had a CCE of over $16/MBtu.

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[11] P. Witte, personal communication, December 1990b.

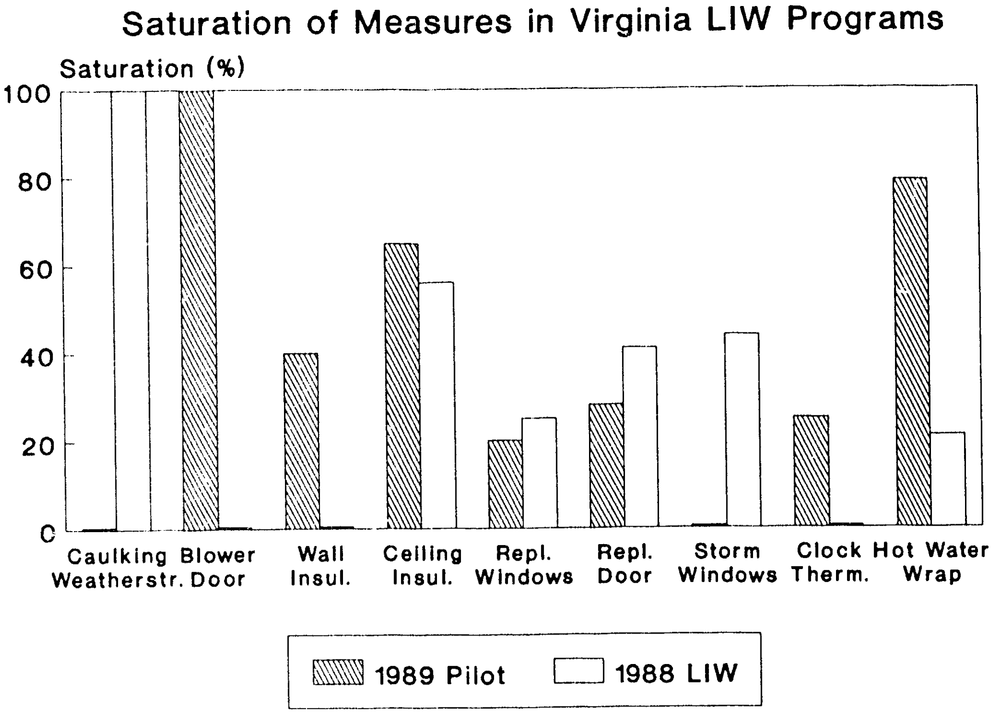


Figure 11. Saturation of measures in the 1988 Virginia low-income weatherization program and the 1989 pilot (Randolph et al. 1991).

The revised protocol emphasized high density cellulose wall insulation, ceiling insulation, and blower door guided sealing of the foundation area and attic bypasses. The protocol stresses addressing these infiltration sites since blocking infiltration sites at the top and bottom of the house reduces infiltration from the stack effect.[12] Air exchange in the neutral pressure plane (e.g. around windows) has less of a driving force as there is little pressure difference across the shell at this point. Also, high-density wall insulation seals many of these sites. Some window replacements were done in the field, though this was not recommended in the protocol. The 43 homes in the pilot program achieved NAC savings of 24 MBtu/year (16%) and a CCE of only $4.50/MBtu. Average expenditures were approximately $1,000 in both sets of homes, but savings increased by a factor of three using the new protocol. With more practice in airsealing techniques and a better adherence to the protocol measures, crews would probably improve further improve the cost-effectiveness of their work.

In terms of program economics, all three demonstration programs were significantly more cost-effective than the original programs. For Minnesota and Michigan which were already running relatively sophisticated programs, cost-effectiveness increased by factors of 1.7 and 1.8 respectively. Virginia started with a basic weatherization program and was able to improve cost-effectiveness by a factor of 3.6. The saturation of wall insulation and clock thermostats was increased in all three programs and storm window installations were reduced or eliminated entirely. Wall insulation was installed in at least 40% of the houses in each program. Ceiling insulation continued to be installed in high saturations as well.

12 The stack effect refers to the pressure gradient due to buoyancy difference between cool and warm air.

5.3 Low-Income Weatherization Programs that Target High Users

Another approach to improving the cost-effectiveness of low-income weatherization programs is to target households with high energy consumption. The correlation observed between high initial consumption levels and achievement of significantly higher energy savings from weatherization has been noted in several studies (Kinney et al. 1990, Shen et al. 1990, Carmody 1986). We discuss results from two low-income weatherization pilot programs that specifically targeted high users (the Michigan Home Repair and Weatherization Program (Kushler and Witte 1987) and Project Choice, carried out by the Minneapolis Energy Office (Quaid and Faber 1988)) and compare them with standard low-income weatherization programs from the same states and similar time periods.[13] Not surprisingly, the high-users lived in much larger homes on average than participants in standard low-income weatherization program (1600 vs. 900 ft^2; see Table 5). Even after adjusting for floor area, the targeted Michigan homes had higher heating energy consumption, while space heating intensities were comparable in the Minnesota homes. Also, space heating intensities were twice as high in the Michigan homes compared to homes in Minnesota, which suggests a larger potential for cost-effective weatherization.

Table 5. Targeting high energy users in low-income weatherization.

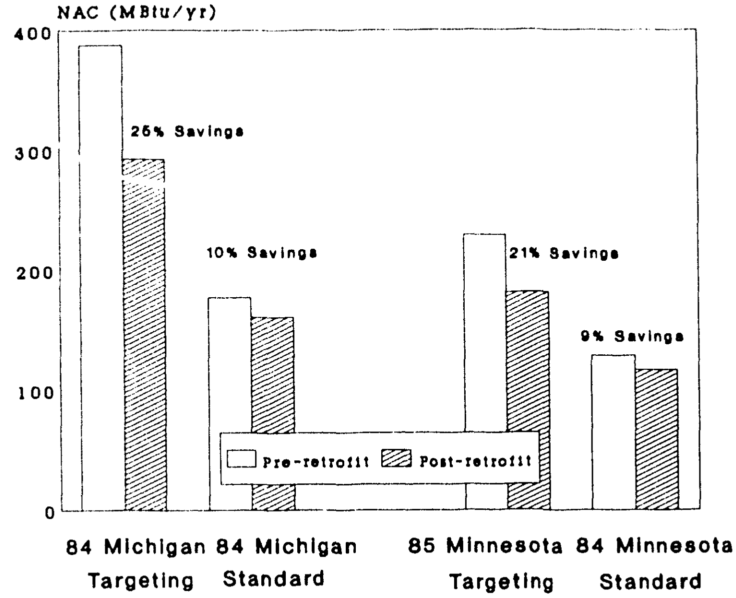
Program	Label	Number of homes	Cond. Area (ft^2)	Pre-Retro. Use (MBtu/yr)	Space Heating Intensity (Btu/ft^2-HDD) Before	Space Heating Intensity (Btu/ft^2-HDD) After	% NAC Savings
Michigan							
1984 Targeted	G074.1	41	1602	322	30.7	21.9	25
1984 Standard	G077.1	155	942	142	22.4	19.7	10
Minnesota							
1985 Targeted	G071.2	13	1600	183	14.3	11.3	21
1984 Standard	G073.1	155	917	103	14.0	12.7	9

The targeting programs spent four times as much as standard weatherization in Michigan and twice as much in Minnesota (see Figure 12).

The targeting programs have lower CCEs in both groups, despite the fact that significant expenditures were spent on repairs not directly related to energy conservation. These results demonstrate that targeting homes by initial consumption can be highly cost-effective, although savings potential must be balanced against other constraints (e.g., the neediness of the weatherization recipients).

[13] The Minneapolis Energy Office (MEO) is now the Center for Energy and the Urban Environment (CEUE).

Targeting High Users vs Standard
Low Income Weatherization Programs



	84 Michigan Targeting	84 Michigan Standard	85 Minnesota Targeting	84 Minnesota Standard
# of Houses	41	155	13	155
Cost (1989$)	4040	1060	2510	1250
CCE (1989$/ MBtu)	4.00	6.90	5.70	9.90

Figure 12. Comparison of average annual savings, retrofit cost, and cost of conserved energy (CCE) for groups of Michigan and Minnesota low-income homes that were high energy users vs. homes that were retrofitted as part of the state's standard low-income weatherization program.

5.4 Comparing Savings in Low-Income Manufactured and Site-Built Houses

In 1986, Jack Laverty, a weatherization program administrator in Ohio stated that: "Retrofitting mobile homes is still in its infancy" (Everett 1986). Judging by the lack of measured data on manufactured ("mobile") home retrofits, this is still the case in 1990. Less than 1.5% of the retrofitted homes in the BECA-B database are manufactured homes despite the fact that they represent 7.8% of the detached single-family housing stock (EIA 1990) and ten percent of all homes eligible for federal Low Income Weatherization Assistance (Beschen 1991).

In 1976, the Department of Housing and Urban Development revised the manufactured home building standards, requiring improvements in insulation levels, which varied by climate. Infiltration is mainly a question of quality control and was not affected significantly by the 1976 standards. Thus, post-1976 manufactured homes tend to be somewhat better insulated than their predecessors, but are still very leaky. Modern manufactured homes continue to have less insulation and much higher infiltration rates than site-built homes, which is partly attributable to manufacturer's emphasis on low-first cost and the difficulty of transporting and setting up the building without compromising the thermal integrity.

For six low-income weatherization programs, we had information to compare results from retrofitting both site-built and manufactured homes. Energy savings and installed retrofit costs are shown in Table 6. The last three columns of the table give ratios of manufactured home to site-built retrofit expenditures, energy savings, and energy saved per dollar invested, which help explain why low-income site-built homes are being weatherized more cost-effectively than manufactured homes. Installed retrofit costs are somewhat lower in low-income manufactured homes compared to site-built homes, ranging from 38% to 82% of retrofit costs in Michigan and Minnesota respectively. However, gas savings are dramatically less, ranging from 12-56% of those observed in site-built homes. The ratio of energy saved per dollar invested (ΔE/retrofit cost) in manufactured homes versus site-built homes ranges from 0.15 to 0.73 in these six programs.

Table 6. Savings and retrofit costs in low-income site-built and manufactured homes.

Program	Housing Type	Number of Units	Retr. Cost (1989$)	NAC Savings (MBtu/ yr)	NAC Savings (%)	Mfd. Home/Site-Built Ratios: Retr. Cost	ΔE	ΔE/Retr. Cost
1981 MN	Site-built	239	1110	23	14	0.82	0.56	0.68
	Manufactured	35	910	13	10			
1984 MN	Site-built	155	1250	12	9	0.76	0.25	0.33
	Manufactured	28	950	3	3			
1984 MI	Site-built	155	1060	17	-	0.38	0.24	0.63
	Manufactured	47	410	4	-			
1986 CA	Site-built	5920	570	5	8	0.78	0.12	0.15
	Manufactured	671	450	0.6	1			
1987 OH	Site-built	8912	540	12	9	0.64	0.17	0.27
	Manufactured	60	340	2	3			
1989 VA	Site-built	43	980	24	16	0.63	0.46	0.73
Pilot	Manufactured	12	620	12	-			

With the exception of the 1981 Minnesota study and the 1989 Virginia pilot, average CCEs for manufactured homes exceed $14/MBtu (see Figure 13). In contrast, average CCEs for site-built homes range from $4.5-11/MBtu.

In addition to these six studies, LBL found two other program evaluations - the Corporation for Ohio Appalachian Development (Label M027.1 in Table 7) and the Illinois Home Weatherization Assistance Program (Label G081 in Table 7) that looked only at savings in manufactured homes (Laverty 1989; Bournakis 1989). Results for all these studies are summarized in Table 7. Average savings for manufactured homes that participated in the Ohio and Illinois studies ranged from 3-6%, and CCEs were high (>$20/MBtu).

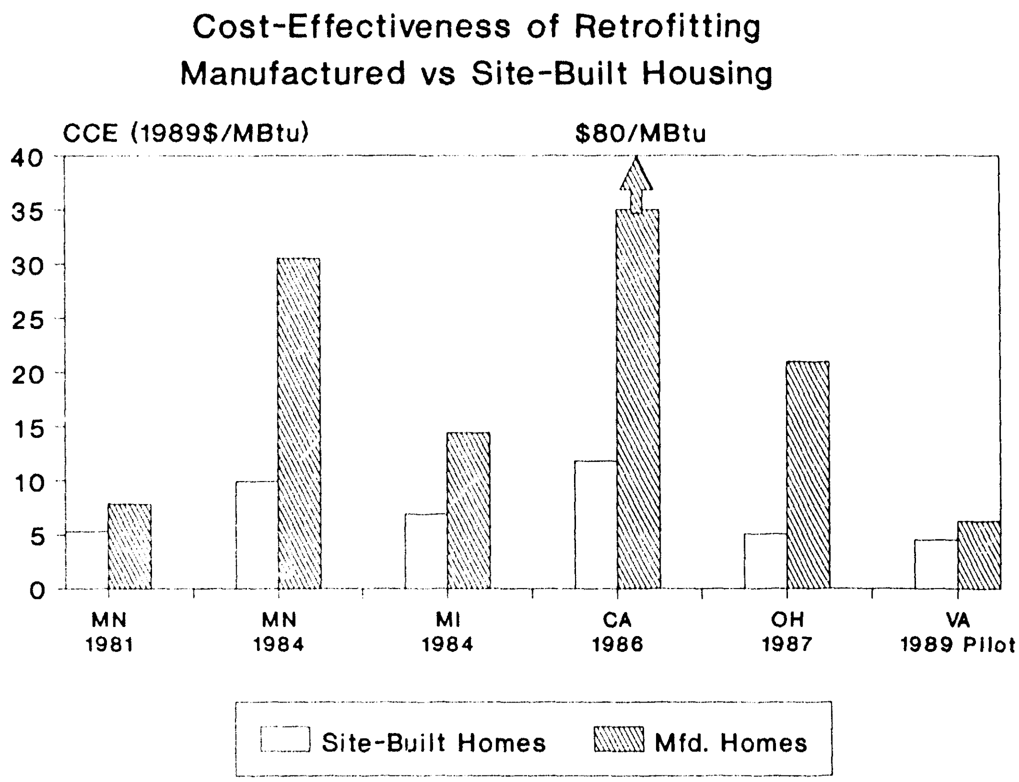


Figure 13. Average cost of conserved energy (CCE) for groups of site-built and manufactured homes from evaluations of Minnesota, Michigan, California, Ohio, and Virginia low-income weatherization programs.

Table 7. Gas-heated manufactured home retrofits.

Label	Year/ Project	No. of Houses	Retrofit Measures	Normalized Annual Consumption Pre-Retro. (MBtu)	Average Energy Savings (MBtu)	Average Energy Savings (%)	Retro. Cost (89$)	Simple Payback (Years)	CCE (1989$/MBtu)
G065.2	1981 MN LIW	35	HS,IA,IF	122	13	10	910	11	7.80
G073.2	1984 MN LIW	28	CW,IA,WM	117*	3	3	950	45	31.00
G077.2	1984 MI LIW	47	CW,WM	98	4	4	410	15	14.00
G081	1986 IHWAP	227	WR,IF,T	86*	6	6	1160	36	20.00
M027.1	1986 COAD	99	CW,SK,RD,WH,HS,WM	70*	2	3	870	41	56.00
G072.2	1986 CA LIW (PG&E)	671	IA,CW,ID	52*	0.6	1	450	145	82.00
G061.2	1987 OH LIW	60	CW,WM	67	2	3	340	40	21.00
O028	1989 VA LIW Pilot	12	PI,SD,WR,RD,WH,IF		11		620	9	6.20

Label: Letter refers to fuel used as main space heating fuel, G = Gas, M = Mixed fuel, O = Oil.

Summaries of studies are arranged by label in Volume II of this report.

RETROFIT MEASURES

Measures are listed if they were installed in 20% or more of the sample.

CW	Caulk+weatherstrip	HS	Heating system retrofit
IA	Attic insulation	IF	Subfloor insulation
ID	Duct insulation	RD	Replace doors
SK	Mobile home skirting	T	Clock thermostat
WH	Water-heating retrofit	WM	Window management (storm windows)
WR	Window replacement	SD	Seal ducts

Project Name

LIW = Low Income Weatherization
IHWAP = Illinois Home Weatherization Assistance Program
COAD = Corporation for Ohio Appalachian Development
PG&E = Pacific Gas and Electric

NAC_{pre} and savings = Weather-normalized annual consumption prior to retrofit and savings of space heat fuel. Projects that use PRISM in energy analysis are indicated by *.

The simple payback period is calculated using nominal retrofit costs and local energy prices.
CCE = Cost of conserved energy (calculated using a 7% discount rate).

In analyzing factors that contribute to the low savings being achieved in manufactured homes, Judkoff et al. (1988) concluded that "Unfortunately, the vast majority of weatherization providers still treat manufactured homes like site-builts. The results ... suggest that this is extremely ineffective." Results from these studies indicate that manufactured homes require *different techniques and measures* than site-built homes in order to improve weatherization cost-effectiveness. Among the six weatherization programs, it appears that only in Minnesota and Virginia were significantly different measures installed in manufactured homes compared to site-built homes (based on available information). In Minnesota, the manufactured homes received less attic and wall insulation, and more furnace work and floor insulation. In Virginia, extensive sealing and duct work was performed based on blower door tests. Large leaks in the duct work and disconnected sections were found to be common. Other measures installed in manufactured homes did not necessarily follow to the protocol developed by the Virginia Center for Coal and Energy Research for site built houses. For example, floor insulation was installed in only 25% of the homes, while over 75% of the houses received window and door replacements (which were not common retrofits in site-built homes). The average CCE of $6.20/MBtu was the lowest for any group of retrofitted manufactured homes. Note that due to access problems in manufactured homes, measures such as floor insulation can never be installed in all the homes.

The Solar Energy Research Institute (SERI) has conducted a series of tests on manufactured homes in a warehouse. While this data does not meet the BECA criteria of occupied housing, their findings are quite interesting and so we briefly describe them. Blower door guided infiltration reduction and duct repair, wall insulation, roof blow, belly blow,[14] and storm windows reduced the building heat-loss coefficient of a test home by 53% (Judkoff 1991). These results, under controlled conditions, probably represent an upper bound on the potential to reduce space heating. They also suggest that it is possible to do significantly better, in terms of actual savings in the field, than is currently achieved in manufactured housing by most weatherization programs.[15]

Based on our limited set of data from occupied homes, we are unable to compare different approaches to weatherizing manufactured homes. However, based on our review of the literature, we found three groups - Solar Energy Research Institute (SERI), the Corporation for Ohio Appalachian Development (COAD), and the Underground Space Center at the University of Minnesota - that have published recommendations on weatherizing manufacturing homes based on their work (Judkoff et al. 1988, Laverty 1989, and Copp 1989). The recommendations from these three groups for weatherizing manufactured homes located in cold climates are remarkably uniform. For example, *blower door guided envelope and duct tightening* was recommended as the first priority in all three studies. Heating system duct leaks are a major source of losses that should not be overlooked. The use of a blower door is considered essential to cost-effective infiltration reduction in manufactured homes because they are leakier than site-builts and

[14] Belly blow is blown-in floor insulation.

[15] Decreases in building heat-loss coefficients can not be directly compared to the percentage decreases in space heat fuel that are reported in program evaluations.

infiltration locations are difficult to locate. *Belly insulation* was recommended as the second measure as it can reduce and seal some heating duct losses as well as reduce conductive losses through the floor. Other measures such as wall and ceiling insulation, furnace work, or measures specific to hot or humid climates may become cost-effective as new techniques are developed specifically for manufactured homes.

The Solar Energy Research Institute (SERI) is currently involved in a demonstration project that is testing these recommended guidelines in 80 manufactured homes in Colorado. Results from this project should be available by late 1991. We are not aware of any other large-scale demonstrations that are systematically examining methods for improving weatherization practices in manufactured homes. A demonstration project that focuses on optimal weatherization techniques for manufactured homes across several climate zones is certainly needed.

Finally, given the difficulty of cost-effectively retrofitting manufactured homes, current standards for new manufactured homes should be re-examined. Higher insulation levels should be considered, given the difficulty of access for retrofitting wall and ceiling insulation. High infiltration rates would still be a problem and one solution may be to require an on-site blower door test for all new manufactured homes, with the contractor being responsible for meeting a minimum air tightness criteria.

5.5 Weatherization Program Recommendations

In this section, we attempt to synthesize lessons from more successful low-income weatherization programs that can be applied to improve the cost-effectiveness of other programs. Our analysis draws upon the M200 Enhanced Low-Income Weatherization Demonstration Project (Shen et al. 1990) from Minnesota, lessons from evaluations of the Michigan (Kushler 1987) and New York weatherization programs (Kinney et al. 1990), and a study prepared by Schlegel, McBride, and Thomas (1990). We include a list of general guidelines and recommendations that program administrators and evaluators felt contributed to the particular success of their programs.

5.5.1 Program Design and Implementation

- Energy saved and cost-effectiveness, rather than units weatherized, should be the primary performance indicators for weatherization programs. An emphasis on weatherizing the maximum possible number of homes leads to installation of capital-intensive measures in order to quickly reach the expenditure limit and move on to the next house. Cost-effective, labor-intensive retrofits, such as blower door guided infiltration reduction and wall insulation are likely to be neglected.
- To the extent possible, weatherization programs should target homes that are high energy users or at least spend more money in these homes. These homes are likely to have the largest savings potential, and can maximize benefits for dollars invested. Weatherization programs that install the same package of measures (or spend the same amount) in all homes are likely to produce sub-optimal results.

- Weatherization auditors need to be given the flexibility, training, and resources necessary to do a proper job. The auditor should have records of all fuel use for the house broken out by the baseload and weather-sensitive components so that after inspecting the house and interviewing the clients, he/she can estimate space heating intensity and water heating use. Energy use data coupled with a visual inspection of the house and some simple measurements such as conditioned area, a blower door test and a furnace inspection is enough information for a knowledgeable auditor to choose the proper retrofits for the house. Proper training in diagnostics and retrofit installation techniques for weatherization crews is also essential.
- Client education is important because many retrofit measures, in particular warm room zoning, depend on proper use by the clients. Heightened energy awareness may lead the clients to save additional energy through behavioral modifications.
- For heating system retrofits, consideration should be given to allotting some money for maintenance work. O&M activities such as changing filters and biennial cleaning and tuning will help ensure persistence of savings at minimal cost.
- Weatherization programs should correct existing safety problems and not cause any new ones. Furnaces should be inspected for safety problems such as blocked flues, improper venting or cracked heat exchangers, especially before reducing infiltration. Homes should not be sealed so tightly that indoor air quality or moisture becomes a problem. In high radon areas, radon levels should be tested before infiltration reduction so that subsequent infiltration work can focus on blocking air leaks that bring radon into the house (e.g., foundation cracks and attic bypasses).
- Periodic process and impact evaluations are crucial to improving program performance. Evaluation needs to be a core component of a weatherization program, rather than an afterthought. It is quite difficult to collect data retroactively, especially for low-income populations which tend to be quite mobile. Evaluations that are planned retroactively are likely to be more expensive and have more significant data gaps. The initial program evaluation will typically be the most difficult; subsequent evaluations can be institutionalized.

5.5.2 Technical Options

Recommendations on specific measures for low-income weatherization are drawn from successful programs as well as other studies on individual retrofit measures (see Chapter 4). Our list of measures is not exhaustive and excludes some low-cost measures, primarily because of lack of measured data. These recommendations should be regarded as general guidelines because the optimal set of weatherization measures will vary depending on individual and stock house characteristics and climate.

- Blower door-guided infiltration reduction and infrared scanning can result in significant savings at reasonable costs, particularly if cutoff cost-effectiveness criteria are used. Locating and sealing bypasses with a blower door is critical, and can improve the effectiveness of other building shell measures (e.g., attic insulation). In general, unguided caulking and weatherstripping will only find the most obvious air leaks, though some successful programs, such as Michigan's, do not use blower doors.

- High-density blown cellulose wall insulation produces significant savings and can be highly cost-effective in severe heating climates when installed by properly trained crews (CCE = $3.60/MBtu for our one LIW program data point). Insulating walls in this manner often reduces infiltration so that further airsealing is unnecessary.
- High-efficiency condensing furnaces are cost-effective to install in cold-climate states if existing furnaces are near the end of their useful life. Even in retrofit applications (as opposed to replacement market), the economics of condensing furnaces have improved as installed costs have been reduced (e.g., as low as $1,500-$1,700 in Wisconsin). In some state programs, this has resulted in somewhat less emphasis on more conventional furnace retrofits (e.g., power gas burners) that cost $500-$700, but save less energy than a condensing furnace.
- Additional attic insulation is a relatively low-cost measure that produces substantial savings. It is a cost-effective retrofit, even in cases where the climate is fairly mild or there is some existing insulation.
- The economics of low-cost water heating retrofits (e.g., tank and pipe wraps and low-flow showerheads) are extremely attractive and these retrofits should be installed as a package.
- Ducts are commonly neglected sources of losses and, with returns, a possible safety issue. In homes with leaking or disconnected ductwork, substantial savings can be achieved at low cost.
- Storm windows and doors and replacements doors and windows are rarely the most cost-effective remaining option, although they offer non-energy benefits that are attractive to occupants.
- Cost-effective electricity and gas savings measures should be combined in the same program. For example, in a gas-heated home, compact fluorescents should be installed in locations where they have a high duty factor.

These measures and strategies have been demonstrated to be "winners" based on measured results; additional retrofit options will surely emerge as cost-effective strategies with increased emphasis on monitoring and evaluation. A key challenge for low-income weatherization is to transfer and adapt lessons from those states with state-of-the-art programs to regions that are lagging behind current best practice.

5.6 Reporting Weatherization Evaluation Results

The context (e.g., audience, purpose) and reporting requirements for program evaluations vary widely. In preparing this report, we found many examples of program evaluations that had collected extensive data, but had not included key elements in published reports. Much of the data used in our analysis had to be obtained directly from the original evaluator or in some cases was estimated when the information was never collected or no longer available. Schlegel and Pigg (1989) have formulated a useful standard for reporting weatherization results, which we expand upon in this section. In addition, given the lack of data from regions with mild climates, we comment on some of the pitfalls that evaluators may encounter as they examine retrofit performance in mild climates.

5.6.1 Retrofit Evaluations in Cold Climate States

Table 8 lists the information that we consider most essential to report for all programs. Inclusion of this type of information facilitates comparative analysis among programs and allows results from one program to be extrapolated to different regions.

Table 8. Information Reporting Guidelines

Program Characteristics	Housing Characteristics	Energy Consumption
• Eligibility requirements • Saturation, cost of measures • Program delivery mechanism • HDD (specify base)	• Housing type • Conditioned area • Type, eff. of furnace • Shell R-values • # of occupants	• End uses included • Monitoring technique • Weather norm. method • Data screening criteria • Pre-retrofit consumption broken down by enduse • % and absolute savings • Space heating intensity (Btu/ft^2-HDD)

Costs	Economics
• Materials • Labor • Administrative	• Simple payback • Cost of conserved energy • Net present value (specify lifetime, discount rate, fuel price escalation rate)

A description of program characteristics provides a useful context for readers: who is eligible for the program, the saturation of retrofit measures, the program delivery mechanism (contractor or agency), and climate severity. The base for heating degree days should be clearly specified in reporting space heat energy intensities (Btu/ft^2-HDD) for a group of houses. Analysts tend to report energy performance normalized to either $base_{60}$ or $base_{65}$ heating degree days. Climate data for U.S. sites available from the National Oceanic and Atmospheric Administration (NOAA) are typically given in $base_{65}$, although $base_{60}$ may be a better choice in terms of an aggregate reference temperature to be used for the entire housing stock. Assuming 8°F of "free heat" from internal gains, using $base_{60}$ heating degree days implies that a house is maintained at 68°F. Better insulated homes will have more degrees of "free heat" from internal gains. We used $base_{65}$ in normalizing estimated space heat energy consumption because of convenience (it was the most widely reported value and for many studies in a range of heating degree days, it would have been impossible to convert the reported $base_{65}$ values to $base_{60}$).

Building characteristics should include conditioned area, insulation levels, the type and efficiency of the heating system, air exchange rates, and the number of occupants. Results should be disaggregated by housing type (i.e., single-family, manufactured houses, and multifamily buildings) because different retrofit strategies are most effective for each housing type. Subsets of results may also be useful: houses that installed a particular retrofit or used different delivery mechanisms.

Overall program costs should be broken down into material, labor, and administrative portions. This facilitates analysis of significant differences in program cost elements and is particularly important if the focus of analysis is on retrofit performance and cost-effectiveness. It is also worth noting whether services were provided by a weatherization agency or a private contractor since contractor rates include profits, while agency rates do not. Data on costs for individual measures are useful and attention should be given to reporting costs of measures that are not easily expressed in discrete units (e.g., caulking and weatherstripping).

The fuel for each key end use (i.e., space heating, hot water, and cooking) should be noted. Energy consumption results should clearly specify what end uses are included and what method was used to collect and weather-normalize data. If available, information on the space heating and baseload consumption should be reported as well (e.g. PRISM breakdown where applicable). Both percentage and absolute savings are important, as savings often depend heavily on initial consumption.

Weatherization evaluations use a variety of economic indicators in assessing cost-effectiveness (simple payback time, cost of conserved energy, net present value, and benefit to cost ratios). In order to interpret results, key input assumptions that underlie the economic analysis should be explicitly stated: absolute savings, discount rate, economic lifetime of measures, fuel prices, and assumed fuel price escalation rate.

Both mean and median values are commonly used in reporting results. For small samples, median values are a better choice, as households that are extreme outliers can have a large effect on average savings. It is also important to be explicit about the treatment of homes that are so-called "negative" savers (homes in which consumption increased in the year after retrofit and which typically received few measures). It is not uncommon for 10-15% of the homes in a large sample to report no or "negative" savings based on billing data analysis. Either the mean or the median is appropriate, but a frequency distribution with both the mean and the median presents the most information. For reporting statistical confidence, we suggest the approach favored by Schlegel and Pigg (1989). List the range with a 95% confidence level, e.g. 15%±5%.

5.6.2 Weatherization Evaluations in Cooling and Mild Climates

Retrofit evaluations in mild climates or climates with significant cooling loads present additional problems. Experience is more limited and analytical techniques are not well refined for estimating cooling savings from billing data. In mild and cooling climates, both heating and cooling use vary tremendously from one household to the next. The savings that are being measured are often less than the noise in the signal. Additionally, different occupants tolerate significantly different indoor temperatures. Thus, it is important to monitor indoor temperature and, if monitoring whole-house energy consumption, use a weather normalization program such as PRISM that has a variable reference temperature. Nonetheless, R^2 correlations will be worse than in cold climates, consumption in some fraction of the houses may not be particularly sensitive to weather (raising questions about model specification errors), and large sample sizes may be critical (given smaller expected savings and variance in savings). If savings cannot be reliably determined from billing data, end use metering and indoor temperature measurements may be essential to develop a realistic estimate of savings or at least calibrate results in a subset of larger samples with billing data.

Cooling retrofits present additional difficulties. Normalizing cooling consumption is problematic as it depends heavily on two variables: cooling degree days and humidity. Also, the load on the air conditioning system is significantly affected by many variables other than climate. Landscaping may affect air conditioning consumption by 25-80% (Meier 1990). Proper design (overhangs, window placement etc.) and occupant manipulation of curtains and use of fans are also significant factors. Thus, merely normalizing cooling energy by cooling degree days is likely to produce a poor correlation. Due to the above list of factors, annual cooling energy use for a group of houses in a similar climate often exhibits tremendous variation. To illustrate, Figure 14 shows the pre-retrofit air conditioning consumption of 25 homes in Palm Beach County Florida (Parker 1990). Even after normalizing by the conditioned area, average annual cooling energy use varies by more than a factor of 20.

Different information needs to be collected and reported in cooling climates to explain results. Indoor temperature, ceiling insulation levels, occupant manipulation of blinds, landscaping, and thermal mass can all cause significant variation in cooling loads experienced by the structure. If data are not being submetered, collect information on all electric enduses. For example, swimming pool pumps can use as much as 3,000 kWh/year. Due to the large variations in energy consumption, averages, medians, and ranges should all be reported. Mild and cooling climate retrofit evaluations present new challenges for evaluators as they require different approaches; however, analytical techniques are being developed in R&D studies of individual measures that can be used and adapted for full-scale program evaluations.

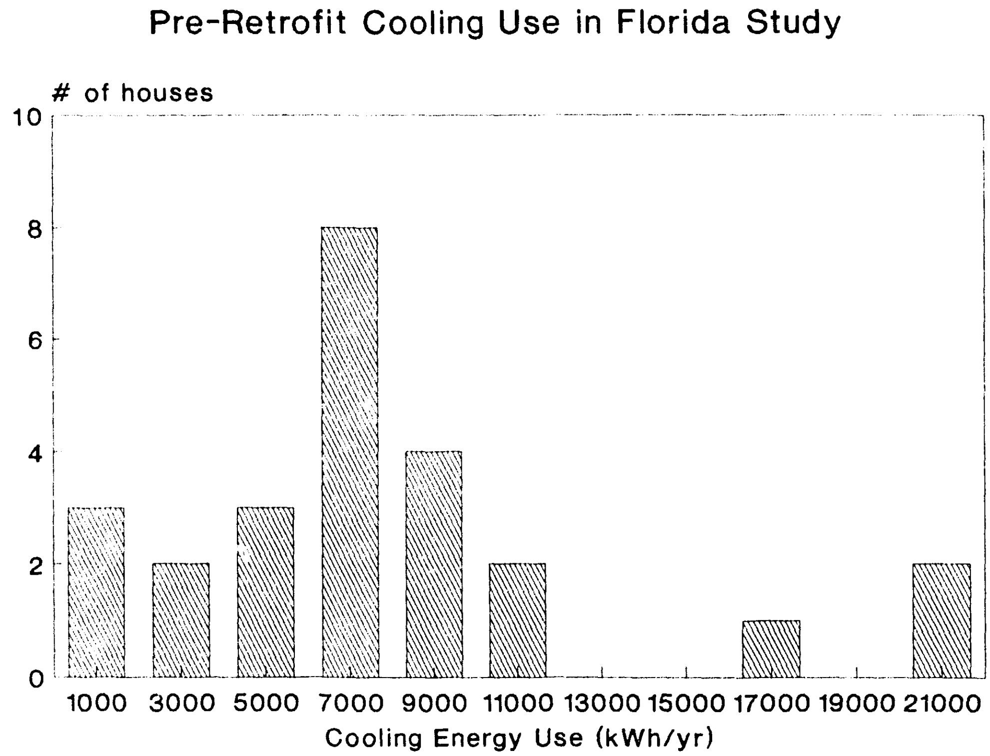


Figure 14. Pre-retrofit air-conditioning energy use for 25 homes in Palm Beach County, Florida. Consumption ranges from 144 kWh/yr to 21,934 kWh/yr, with a median of 7,325 kWh/yr. The coefficient of variation is 65% (Parker 1990).

6. UTILITY-SPONSORED WEATHERIZATION PROGRAMS

6.1 Overview

In this chapter we discuss results from evaluations of electric and gas utility conservation programs. These programs typically focused on reducing energy used for space heat and (to a lesser extent) hot water. The first generation of these large-scale utility weatherization programs began in the late 1970s and was successful in achieving high penetration rates for conventional envelope insulation and infiltration measures. Results were particularly well-documented for electric heat customers in the Pacific Northwest and in the region served by the Tennessee Valley Authority, and for gas-heat utility customers in several states (e.g., California, Colorado, Michigan). For example, the Northwest Power Planning Council (NPPC) estimates that about 340,000 single-family homes have been weatherized in its four-state planning region in the last ten years and that about 300,000 eligible homes have yet to be weatherized (Eckman 1990).[16] These large-scale, aggressive programs contributed to the widespread view that many of the shortest-payback measures were reaching saturation in existing single-family homes. However, even in the Pacific Northwest, there is significant potential to increase the energy efficiency of the existing single-family housing stock.

In the early 1980s, many gas utilities scaled back their programs as gas supplies become more abundant (i.e., the "gas bubble") and the effects of an economic recession and other factors resulted in slow or no growth in gas demand. Similarly, most electric utilities reduced their weatherization efforts in regions with excess capacity (e.g., California) or energy surplus (e.g., the Pacific Northwest). Where utilities continued to provide traditional envelope retrofit (weatherization) programs, these were often restricted to low-income households, and generally were not closely monitored or evaluated.

During the 1980s, many utilities have shifted the focus of their residential demand-side management (DSM) programs to load management and appliance rebate programs. These programs have grown rapidly; a recent EPRI study estimated that nearly 15 million residential customers are participating in some kind of DSM program. Of this total, over three million customers are on load control programs, up from one million in 1977 (EPRI 1990). While utilities increasingly analyze the effects of these programs, the evaluations typically do not meet the minimum data quality requirements necessary for inclusion in the BECA database. For example, appliance rebate programs (e.g., high-efficiency refrigerators and air conditioners) generally rely on equipment efficiency ratings (using the DOE test procedures) and engineering estimates of savings; few studies report savings based on metered data. In addition, utilities typically only have records of utility program costs (customer rebates and administrative expenses) and do not report data on additional costs paid by the customer.[17] For evaluations of load management programs, some utilities report peak load reductions based on metered data, although most tend to rely on engineering estimates. Often, evaluations of these programs tend to focus most of their

[16] Eligible homes are assumed to be those built before 1980.

[17] Rebates often do not cover the full incremental cost of the high-efficiency appliance compared to the standard model.

efforts on determining the number of "free riders", those customers that would have purchased an efficient appliance or kept the air conditioner off without the utility's rebate. For ease of comparison, we decided to restrict the BECA-B database to utility programs whose strategic objective is energy efficiency. Other BECA databases compile and analyze information on appliance performance (e.g., water heating and refrigerators) and load management technologies drawn from utility-sponsored DSM programs (Usibelli 1984; Meier and Heinemeier 1988; Piette and Wyatt 1988).

6.2 Gas Utility Weatherization Programs

Table 9 summarizes results from weatherization programs conducted by gas utilities. The studies are ordered chronologically and arranged into two groups, in order to highlight differences in eligible population (i.e., general housing stock vs. low-income homes) and extent of weatherization. Programs implemented prior to 1982 typically were open to all eligible households or targeted high users (e.g., Consolidated Gas in Michigan), while recent programs tend to be restricted to low-income residents, often as a result of a PUC mandate. In the five pre-1980 studies, gas utility programs focused almost exclusively on installation of attic insulation, while later programs offered a wider range of retrofit options. In these early ceiling insulation programs, average gas consumption decreased by 12-31 MBtu/year (6-21% NAC savings) and retrofit costs were under $700 in 1989$ (see Figure 15). These retrofits were cost-effective even in mild climates, having CCE values ranging from $1.80/MBtu to $4.40/MBtu (Proudfoot 1979; McLenon 1981; Thornsjo 1980; Williams 1980).

The post-1980 gas utility weatherization programs offered a much wider range of measures including wall and floor insulation, window retrofits, hot water and heating system measures. Our analysis suggests that homes that participated in these later programs tended to use less energy for space heating prior to retrofit, as indicated by the space heating intensity values which ranged from 11-15 Btu/ft^2-HDD. As the list of eligible measures has expanded, average retrofit costs have increased significantly, particularly for those utilities located in cold climates (Minnesota and Wisconsin) that allowed furnace replacements (total retrofit costs averaged $1800-3800 per house). Hirst et al. (1983) found that annual gas consumption decreased by 33 MBtu (19% of the NAC) in a sample of homes that participated in a 1981 Northern States Power (NSP) program (Label G060). Low-income weatherization programs sponsored by utilities in Wisconsin offered similar measures, although a greater fraction of the homes installed attic and wall insulation and fewer homes received caulking and weatherstripping compared to the NSP program (Banerjee and Goldberg 1985, Horowitz et al. 1987). Percent savings were comparable in the Wisconsin programs (17-19% of the NAC), although CCEs were somewhat more attractive than the NSP program ($9-10 vs. $11/MBtu). Pacific Gas and Electric sponsored an evaluation of its 1986 low-income weatherization program which installed attic insulation, caulking and weatherstripping and duct insulation at an average cost of $570 per house (see Label G072.1). The results were somewhat disappointing in a sample of almost 6000 homes; annual energy savings were only five MBtu/year and the CCE was $11.80/MBtu (Cambridge Systematics 1988).

Table 9. Summary of gas utility weatherization programs.

Label	Year State Sponsor	HDD (65° F)	No. of Houses	Retrofit Measures	Normalized Annual Consumption Pre-Retro (MBtu)	Average Savings (MBtu)	(%)	Space Heating Intensity Before (Btu/ft²-HDD₆₅)	After	Retro. Cost (89$)	Simple Payback (Years)	CCE (1989$/MBtu)
General Housing Stock												
G030	74 MI Consolidated Gas Co	6260	71	IA	235	31	13			630	4	1.80
G013	77 CO Public Service Co	6020	33000	IA	157	20	13	15.7	13.1	500	6	2.40
G011	79 MN Northern States Power	8160	84	IA,CW	196	12	6	10.1	9.3	450	8	3.60
G012.1	79 CA Pacific Gas & Electric	2190	33	IA	117	15	13	30.1	24.7	690	6	4.40
G012.2	79 CA Pacific Gas & Electric	2650	16	IA	95	20	21	18.4	12.6	680	4	3.30
G060	81 MN Northern States Power	8010	162	CW,HR,IA,T,DR,IW,WM,WH	169	33	19	10.5[1]	8.0	3770	16	10.90
Low Income Housing Stock												
G082.1	83 WI Utilities	7500	606	CW,IA,HS,IW,HR,IS	149*	29	19	12.4[1]	10.0	2570	11	9.80
G066.1	84 WI Utilities	7500	483	IA,IW,IP,HR,WH,WM,IF,CW	139*	23	17	11.7[1]	9.7	1830	11	8.60
G072.1	86 CA Pacific Gas & Electric	2700	5920	IA,CW,ID	69*	5	8			570	21	11.80
G061.1	87 OH Utilities	6000	8912	CW,WM,IA	135	12	9	15.4[2]	13.6	540[3]	10	5.00

RETROFIT MEASURES

Measures are listed if they were installed in 20% or more of the sample. Summaries of studies are arranged by label in Volume II of this report.

CW	Caulk+Weatherstrip	DR	Storm Doors
HR	Heating System Replacement	HS	Heating System Retrofits
IA	Ceiling/Attic Insulation	IW	Wall Insulation
IF	Subfloor Insulation	IP	Foundation Insulation
IS	Sillbox Insulation	T	Clock thermostat
WH	Water-heating Retrofit	WM	Window Management (storm windows)

NAC_{pre} and savings = Weather-normalized annual consumption prior to retrofit and savings of space heat fuel. Projects that use PRISM in energy analysis are indicated by *.

CCE = Cost of conserved energy (calculated using a 7% discount rate).

The simple payback period is calculated using nominal retrofit costs and local energy prices.

[1] LBL assumed that space heat use was 80% of the NAC in order to calculate the space heating intensities.

[2] LBL assumed that space heat use was 75% of the NAC in order to calculate the space heating intensities.

[3] Costs are low in this study because of significant labor contributions from volunteers.

Note that gas consumption prior to retrofit was much lower in these low-income homes compared to the homes that participated in the utility's pilot attic insulation program in 1979 (69 MBtu/year vs. 95-117 MBtu/year).[18] A low-income weatherization program implemented by utilities in Ohio installed storm windows, caulking and weatherstripping, and attic insulation (Kirksey et al. 1989). Retrofit costs were low ($540 per house) because much of the work was done by volunteers and thus the CCE is not directly comparable to the other programs (see Label G061.1).

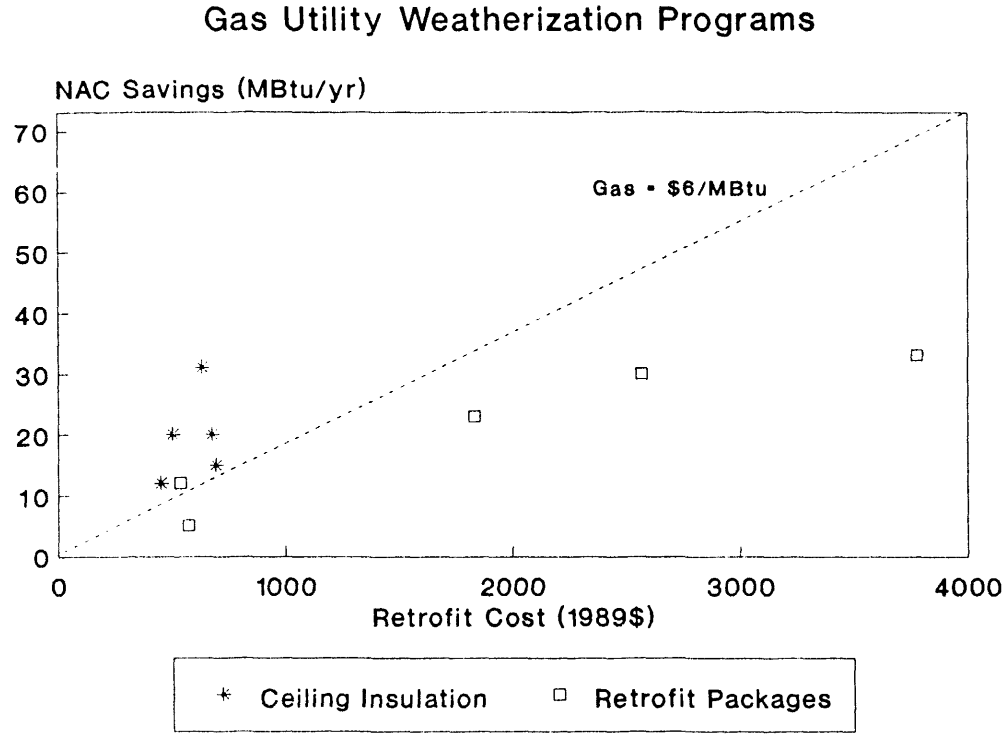


Figure 15. Average annual gas savings as a function of retrofit costs are shown for 10 evaluations of weatherization programs conducted by gas utilities. Sample size represented by each data point ranges from 16 to 33,000 homes and about 50,000 homes are represented. The sloping reference line represents the minimum energy savings that must be achieved, for each level of investment, if the retrofit project is to be cost-effective compared to national average residential prices for gas. The future stream of energy purchases for 15 years (assuming a constant energy price (in 1989$)) is converted to a single present-value, using a 7% real discount rate in order to compare it to the one-time conservation investment. Data points that are above the dashed line have CCEs less than $6/MBtu.

Based on this small sample of gas utilities that have evaluated their low-income weatherization programs, overall savings appear comparable to the standard DOE low-income weatherization program. However, we believe that the cost-effectiveness of these utility-sponsored programs could be improved by drawing upon the experiences of the best low-income weatherization demonstration programs (see Chapter 5). Finally, DSM programs offered by gas utilities are likely to expand during the next decade as gas supplies tighten and more PUCs adapt and mandate integrated resource planning for local distribution gas companies (Hopkins 1990). We

[18] Inadequate data on house size precludes normalization of results by conditioned floor area to account for this key factor.

expect that the next generation of gas utility DSM programs will produce a much larger sample of well-documented results, given the increased emphasis by many PUCs on evaluation (RCG/Hagler, Bailly, Inc. 1990).

6.3 Electric Utility Weatherization Programs

Measured data on weatherization programs conducted by electric utilities is concentrated in those regions of the country where electric heat has a significant market share in the existing housing stock, particularly the Pacific Northwest and the area served by Tennessee Valley Authority. Table 10 provides summary information on the evaluation results from Pacific Northwest utilities: date of installations, number of houses, average electricity consumption and savings, space heat intensity, average retrofit cost, simple payback, and cost of conserved energy (CCE). These utilities emphasized electricity savings (i.e., conservation) as the DSM load shape objective rather than load management primarily because of the region's resource characteristics: electric generation that is hydro-based and energy-limited (rather than capacity-constrained). Electricity prices have been well below the national average (because of the large hydropower resource) and levelized costs for new thermal generating resources are projected to exceed current prices. Because of these low prices, much of the existing stock was constructed rather inefficiently and historically, electricity usage has been quite high (e.g., annual pre-retrofit electricity usage averaged between 21,000-33,000 kWh for homes in these programs).

Except for the Hood River Project (Label E032.1), all of the programs were pilot or full-scale conventional weatherization programs. These first generation programs were implemented during the late 1970s and the early 1980s. In some cases, LBL has disaggregated the results into two or more data points to highlight differences in installed options (e.g., E009.1 for homes that received measures designed to reduce water heating vs. E009.2 for homes that installed only shell options) or to present results from homes weatherized in different program years (e.g., E013.1 to E013.6 - Seattle City Light's Home Energy Loan Program (HELP)). Most full-scale programs offered a wide range of building shell and water heating measures. All programs emphasized attic and foundation insulation, storm windows and low-cost water heating retrofits. Storm doors tended to be more popular in some of the initial programs, while wall insulation and duct retrofits (mainly insulation) were installed more frequently in later programs. Median electricity consumption (NAC) for the 21 data points decreased by 4020 kWh (16%) after retrofit. With the exception of Seattle City Light's initial program (Label E005.1) which was limited to attic and floor insulation, average contractor costs among the programs ranged from $1,300 to $2,800 per house for these packages of measures. For utility weatherization programs conducted prior to 1985, CCEs ranged from 1.4-7.0¢/kWh with the median CCE around 4.4 ¢/kWh for these 16 data points (see Table 10), based on gross savings. CCEs, based on gross savings, are higher for the later programs, but would be lower if net savings were used.

Table 10. Electric utility weatherization programs in the Pacific Northwest.

Label	Year Sponsor Project	No. of Houses	Retrofit Measures	Normalized Annualized Consumption: Pre-Retro (kWh)	Average Savings (kWh)	Average Savings (%)	Space Heating Intensity (Btu/ft^2-HDD_{65}): Before	After	Retro. Cost (89$)	Simple Payback (Years)	CCE (1989¢/kWh)
E007.1	78 PGE Program	300	IA,IF,WM,DR,WH,CW	23640	3940	17			2260	13	5.4
E004.1	79 PP&L Program	973	IA,IF,WM,DR,CW,WH	25420	4460	18	5.6	3.8	2430	8	5.1
E005.1	79 SCL Program	133	IA,IF	30110	4180	14			640	5	1.4
E009.1	79 WWP Program	1030	IA,IF,DR,WM,WH	30010	4450	15			1910	18	4.1
E009.2	79 WWP Program	810	IA,IF,DR,WM	30140	4350	14	7.2	5.5	1830	17	4.0
E016.1	80 PGE Program	208	IA,IF,WM,DR,WH,CW	24490	4040	16	5.4	3.7	2230	12	5.2
E006.1	80 PP Program	6289	IA,IW,IF,WM,DR,T,WH	32800	8580	26	7.2	4.2	1750	5	1.9
E011.1	81 BPA Pilot	179	IA,IF,IW,DR,WM,CW	28500	6000	21	5.4	3.2	2800	18	4.4
E013.1	81 SCL HELP	132	IA,WM,IF,WH,IW,ID,CW	25870*	4340	17	5.8	4.5	2020	16	4.4
E014.1	81 SCL LIEP	293	IA,IF,IW,WH,ID,CW	21060	3040	14	5.5	4.1	1900	23	5.9
E017.1	81 Idaho ZIP	101	IA,IF,IW,WM,ID,CW	23080	2180	9	5.3	4.4	1330	14	5.7
E013.2	82 SCL HELP	116	IA,WM,IF,WH,IW,ID,CW	25950*	4020	15	6.1	4.3	2450	13	5.8
E030.1	82 BPA Program	229	IA,IF,WM,T,ID	27600*	4800	17	5.4	3.8	1980	13	3.9
E013.3	83 SCL HELP	111	IA,WM,IF,WH,IW,ID,CW	24400*	3820	16	5.7	4.4	2320	13	5.7
E030.2	83 BPA Program	248	IA,IF,WM	25400*	2900	11	4.8	3.8	2150	19	7.0
E013.4	84 SCL HELP	108	IA,WM,IF,WH,IW,ID,CW	24930*	5050	20	6.0	4.4	1840	7	3.4
E013.5	85 SCL HELP	285	IA,WM,IF,WH,IW,ID,CW	25180*	2000	8	4.9	4.5	2400	23	11.3
E032.1	85 BPA/PP&L HOOD RIVER	362	WM,CW,IA,IF,IW,T	24400*	4000	16	3.8	2.6	6090	32	14.4
E038.1	85 BPA RWP	239	IA,IF,WR,CW,WM,ID,IW	23860*	2100	9	4.5	3.5	2090	25	9.4
E039.1	86 BPA RWP	252	IA,IF,WR,CW,WM,ID,IW	23400*	1460	6	3.8	3.2	2360	42	15.3
E013.6	86 SCL HELP	278	IA,WM,IF,WH,IW,ID,CW	22770*	210	1	4.6	4.6	2660	228	121
			Median Values (N=21)	25200	4020	16	5.4	4.2	2150	16	5.4

RETROFIT MEASURES

Measures are listed if they were installed in 20% or more of the sample. Summaries of studies are arranged by label in Volume II of this report.

IA	Ceiling/Attic Insulation	IF	Subfloor Insulation	IW	Wall Insulation	ID	Insulate Ducts
CW	Caulk+Weatherstrip	WH	Water-heating Retrofit	WM	Window Management (storm windows)	DR	Storm Doors
T	Clock thermostat						

Sponsoring Utility

PGE	Portland General Electric	PP&L	Pacific Power and Light	SCL	Seattle City Light	Idaho	Idaho Power Company
WWP	Washington Water Power	PP	Puget Power	BPA	Bonneville Power Administration		

NAC_{pre} and savings = Weather-normalized annual consumption prior to retrofit and savings of space heat fuel. Projects that use PRISM in energy analysis are indicated by *.

The simple payback is calculated using gross savings (and nominal retrofit costs). For later programs, net savings are more relevant. (See Table 11).

CCE = cost of conserved energy (calculated using a 7% discount rate). Space heating intensity is given in site energy (1 kWh = 3412 Btu).

Figure 16 shows average space heating intensities before and after retrofit for homes that participated in these programs. Results are arranged chronologically, which highlights the overall trend of declining space heating energy intensity prior to retrofitting. However, this finding should be hedged because of other complicating factors (e.g., early programs may have targeted high users). The median reduction in space heat intensity was about 21% in these 16 programs. More importantly, all of the conventional utility weatherization programs ended up at about the same post-retrofit level - about 4 Btu/ft^2-HDD (site energy), which provides an important programmatic benchmark. Note, that annual space heating use for later programs is determined from PRISM, which typically overestimates the space heating fraction by about 10-20% (Fels 1986b).

Space Heating Intensities in Pacific Northwest Utility Programs

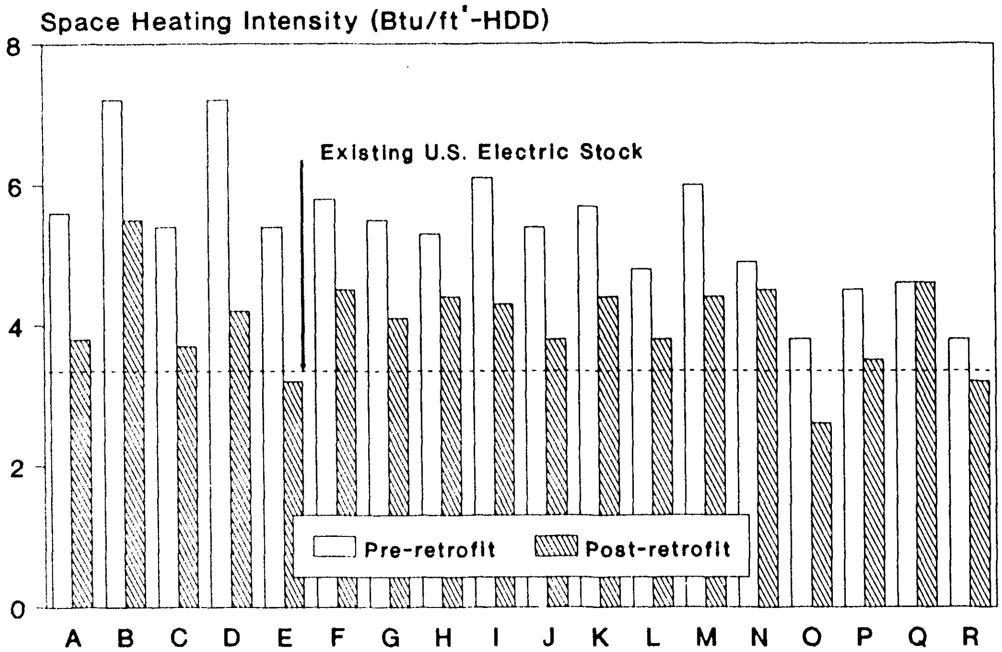


Figure 16. Average space heating intensity before and after retrofit for homes that participated in electric utility weatherization programs in the Pacific Northwest. For comparison, we show an EIA estimate of space heating intensities for U.S. electric-heated stock based on the 1987 RECS survey. Utility programs are arranged chronologically and identified by letters which correspond to the key below.

A	'79 Pacific Power and Light	J	'82 Bonneville Power Adm.
B	'79 Washington Water Power	K	'83 Seattle City Light HELP
C	'80 Portland General Electric	L	'83 Bonneville Power Adm.
D	'80 Puget Power	M	'84 Seattle City Light HELP
E	'81 Bonneville Power Adm.	N	'85 Seattle City Light HELP
F	'81 Seattle City Light HELP	O	'85 Bonneville Power Adm. Hood River
G	'81 Seattle City Light LIEP	P	'85 BPA RWP
H	'81 Idaho Power ZIP	Q	'86 Seattle City Light HELP
I	'82 Seattle City Light HELP	R	'86 BPA RWP

Space heating intensities after retrofit were about 35% lower at Hood River homes, which installed additional insulation and glazing compared to standard weatherization programs. The Hood River Conservation Project (HRCP) was a $19.2 million, five year test of the upper limits of residential energy conservation and was funded by the Bonneville Power Administration and carried out by Pacific Power and Light in Hood River, Oregon (Hirst et al. 1987). Homes were monitored from 1982 to 1986 with most of the retrofits being installed in 1985. The goal was 100% participation of electrically heated homes. Consequently, an extensive package of envelope and water heating measures were installed, generally at no charge to the homeowner. Of all eligible homes in the town, 91% received audits and 85% had major weatherization measures installed. BPA spent an average of $6,100 per house. For single-family homes, the normalized annual consumption (NAC) decreased by an average of 4,000 kWh (16%), while peak demand decreased by 0.48 kW per household. The cost of conserved energy (CCE) was about 14¢/kWh. There are several factors that partially explain why the savings and economics of the demonstration project were not as favorable as predicted. First, many households had participated in earlier conservation programs. For example, single-family homes that had not participated in prior conservation programs saved an average of 4500 kWh compared to average savings of 2200 kWh for those homes that had participated in previous utility programs. Second, compared to the early 1980s, residential electricity consumption was dropping in the region as a result of higher prices and an economic recession. Third, average space heating intensities in Hood River homes were already significantly lower prior to retrofit compared to typical homes that had participated in other utility programs in the region (3.8 vs. 4.1-7.2 Btu/ft^2-HDD, see Figure 16). Fourth, retrofits costs were over $6,000 per house, triple what most other programs spent. The program undoubtedly would have been more cost-effective if some marginal measures had not been installed. However, the overall goals of the project were achieved in that Hood River demonstrated that very high participation rates were possible, that conservation was a viable resource that could be reliably acquired, and that very low space heat intensities could be achieved, which established an efficiency benchmark for retrofits of existing housing (2.6 Btu/ft^2-HDD).

Most of these program evaluations also included control groups of non-participating customers. Control groups were utilized in an attempt to isolate the effects of the utility-sponsored *program* from other factors that affect changes in electricity consumption. For example, electricity prices increased dramatically in much of the Pacific Northwest during the early 1980s. Homeowners presumably altered their energy-consuming behavior and invested in retrofit measures independent of utility programs in response to rising electricity prices. As noted in Chapter 3, some homes in the control group may have installed retrofits independent of the utility program during the monitoring period which contributed to reductions in consumption.

Table 11 provides a comparison of gross and net savings in 19 Pacific Northwest programs (net savings are adjusted for changes in electricity usage that occurred in the control group homes). The median values for annual gross and net electricity savings are 4020 and 2730 kWh respectively among Pacific Northwest utility programs, although there is a large variance across programs and over time. In Figure 17, we plot gross versus net savings, with results grouped into three time periods: pre-1981, 1981-1984, and 1985-1986. Prior to 1981, net savings were generally lower than gross savings. In contrast, the evaluation from the 1985-86 years of Seattle

City Light's HELP program found that electricity consumption had increased significantly in control group homes during the monitoring period and thus, net (adjusted) savings were greater than gross savings. Declining real electricity prices in the Seattle region with a booming local economy is one possible explanation for the underlying increases in household electricity consumption in these control group houses.

Table 11. Gross vs. net savings in Pacific NW utility programs.

Label	Program/ Sponsor	Gross Savings (kWh)	Gross Savings (%)	Net[a] Savings (kWh)	Net Savings (%)	Ratio of Net/Gross Savings
E007.1	1978 Portland General Electric	3940	17	3930	17	1.00
E004.1	1979 Pacific Power & Light	4460	18	3380	14	.76
E005.1	1979 Seattle City Light (SCL)	4180	14	1950	7	.47
E009.1	1979 Washington Water Power	4450	15	2940	10	.66
E009.2	1979 Washington Water Power	4350	14	2840	9	.65
E016.1	1979 Portland General Electric	4040	16	2190	9	.54
E011.1	1981 Bonneville Power Administration	6000	21	2800	10	.47
E017.1	1981 Idaho Power Company	2180	9	1570	7	.72
E013.1	1981 SCL HELP Program	4340	17	2730	11	.63
E014.1	1981 SCL LIEP Program	3040	14	3330	16	1.10
E030.1	1982 Bonneville Power Administration	4800	17	4600	17	.96
E013.2	1982 SCL HELP Program	4020	15	2050	8	.51
E030.2	1983 Bonneville Power Administration	2900	11	2400	11	.83
E013.3	1983 SCL HELP Program	3820	16	2100	9	.55
E013.4	1984 SCL HELP Program	5050	20	2340	9	.46
E013.5	1985 SCL HELP Program	2000	8	2360	9	1.18
E038.1	1985 BPA RWP	2100	9	2200	9	1.05
E013.6	1986 SCL HELP Program	210	1	2440	11	11.62
E039.1	1986 BPA RWP	2360	10	3170	13	1.34
	Median Values (N=19)	4020	15	2730	10	.72

[a] Net Savings = $(NACpost/NACpre)_{control} * (NACpre)_{treatment} - (NACpost)_{treatment}$

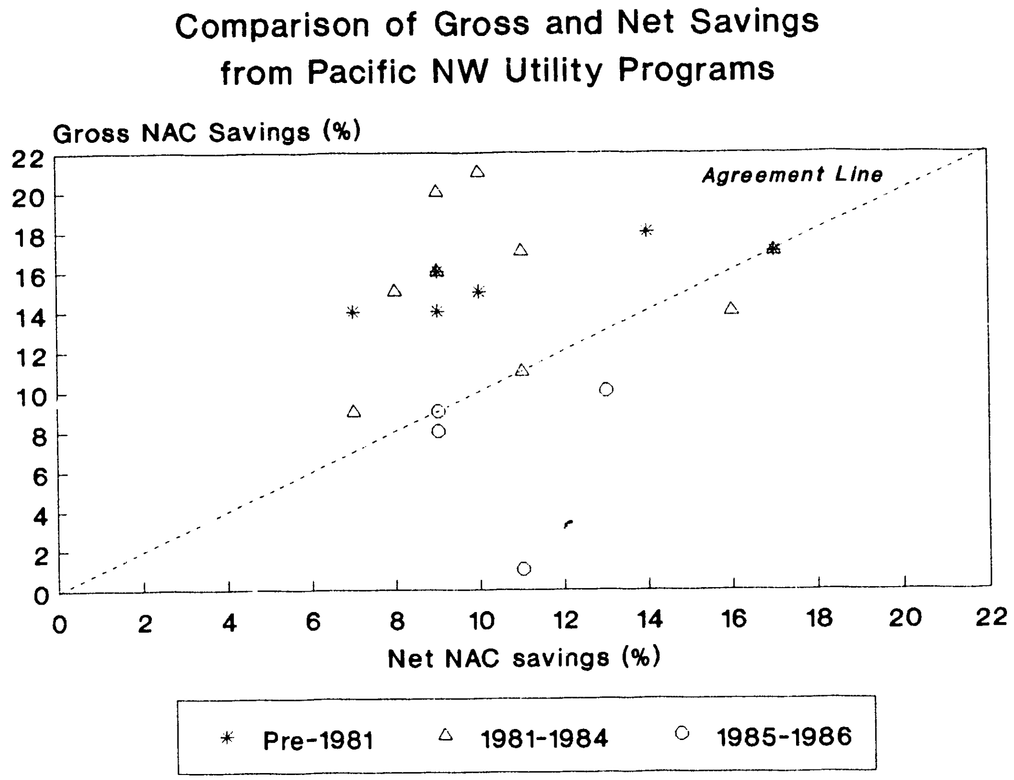


Figure 17. Comparison of gross vs. net savings for the electric utility weatherization programs from the Pacific Northwest that are shown in Table 11. Net savings include an adjustment for changes in electricity consumption that occurred in control group homes during the same time period.

6.4 Persistence of Savings

Most program evaluations are based on analysis of utility bills for only one year after retrofit for groups of participating and non-participating households. However, a few programs, notably the Seattle City Light (SCL) Home Energy Loan Program (HELP) and the BPA Weatherization Program, have monitored electricity consumption in groups of houses for up to seven years. The results are discussed in the next sections.

Seattle City Light (SCL) HELP Program

SCL evaluated its HELP program for six program years (1981-1986) and collected one to six years of post-retrofit data (i.e., up to 1987) for samples of participating homes. The HELP program provided zero-interest loans for residential customers to install envelope measures in electrically heated homes (Sumi and Coates 1988). In addition, SCL monitored consumption changes in a control group of non-participants over this same time period. In Figure 18, we plot average electricity consumption before and after retrofit for each group of participating homes, consumption trends for the non-participants in the control group and local electricity prices (shown by bars). We would make the following points about persistence of savings:

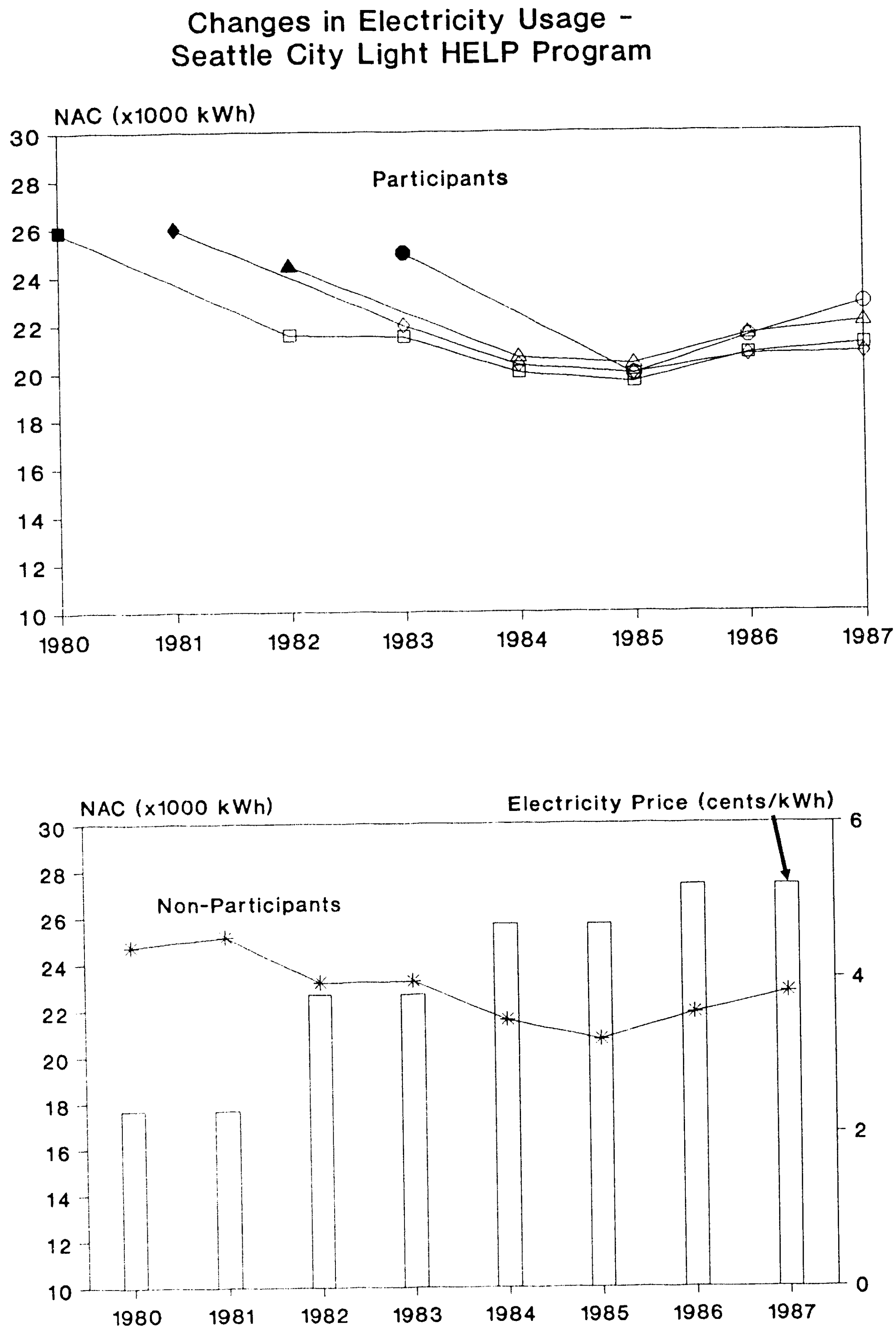


Figure 18. Average electricity consumption (NAC) for groups of homes participating in Seattle City Light's Home Energy Loan Program (HELP) between 1981 and 1982, as well a control group of non-participants (Source: Sumi and Coates 1988). For each group, consumption for the pre-retrofit year is represented by a solid shape, while the open shapes are for the post-retrofit years. The scale for normalized annual consumption (NAC) is plotted on the left vertical axis and ranges from 10,000-30,000 kWh/year. Nominal electricity prices are plotted as bars and correspond to values on the right vertical axis.

- First, the graph suggests that the overall trends in electricity consumption over time have been similar in each group of retrofitted homes: declining usage in 1983 and 1984, with some increases in consumption between 1985 and 1986-87.
- Second, the sharp price increase that occurred in 1981 (65%) induced changes that reduced consumption in the control group homes and presumably also had some effect on homes that were retrofitted in 1981. This trend was also observed in homes that were eventually retrofitted in 1983 and 1984 (not shown in consumption data in Figure 11). In the group of homes that were eventually retrofitted in 1983, consumption decreased by 2,318 kWh (8.7%) between 1981 and 1982 while electricity usage decreased by 1,667 kWh (6.3%) during the same period for the group of homes retrofitted in 1984.
- Third, the increases in consumption that occurred in participating homes in 1986 and 1987 also were observed in control group houses. Control group consumption reached a low in 1985 and increased in 1986 and 1987, by about 900 and 2000 kWh respectively from 1985 levels, suggesting that other factors (i.e., a booming economy and declining real electricity prices) may have accounted for the increased usage rather than a noticeable decrease in the effectiveness of the conservation measures.
- Fourth, for homes retrofitted in 1981 and 1982, the average level of savings in 1987 is still comparable to that achieved in the initial year after retrofit.

Bonneville Power Administration Program

In evaluating the impact of its pilot and full-scale residential weatherization program, the Bonneville Power Administration (BPA) collected several years of post-retrofit billing data from samples of participants and non-participants. This multi-year impact savings analysis was conducted for homes that were weatherized in several program years (i.e., 1981 pilot, 1982-83, 1985, 1986). (Goeltz et al. 1986; M. Horowitz, and P. Degens 1987; M. Haeri 1988; and D. White and M. Brown 1990). Figure 19 shows several years of electricity consumption for participating households that were retrofitted between 1981 and 1986, the average consumption of non-participants in selected control groups, and nominal electricity prices during the period. We would make the following points about the BPA studies:

- Irrespective of pre-retrofit levels, the annual electricity consumption after retrofit is quite similar among the various groups of homes that participated in pilot and full-scale programs in each program year (i.e., about 22,000 kWh).
- Average electricity usage after retrofit among participating homes is relatively flat, with the exception of participants in the 1986 Program where post-retrofit consumption in the third year increased by about 4.5% compared to the first year after the retrofit. Gross savings, which reflect only changes in participant's usage, appear to be maintained for several years after the retrofit.
- When PRISM results are disaggregated into weather-sensitive (mostly space heating) and non weather sensitive (i.e., baseload) components, it turns out that most of the participants' savings come from reductions in weather-sensitive consumption (not shown in figure). This is not surprising given the program's emphasis on various building envelope improvements.

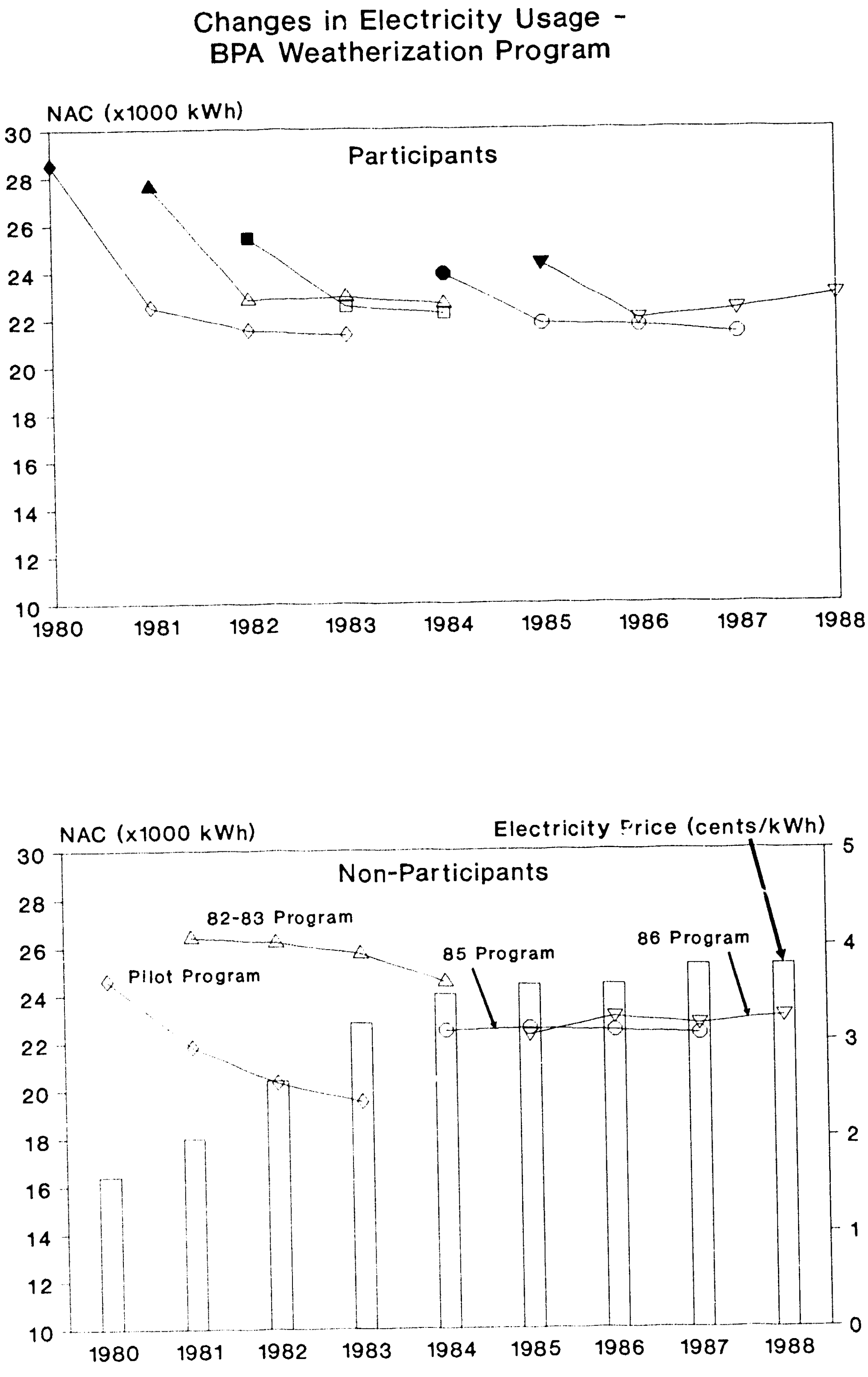


Figure 19. Average electricity consumption (NAC) for groups of participating homes in the Bonneville Power Administration's weatherization programs between 1981 and 1986, as well four groups of non-participants. (Source: Hirst et al. 1985, Haeri 1988, White and Brown 1990). Consumption for the pre-retrofit year is represented by the solid shapes and for the post-retrofit years by the open shapes. The scale for normalized annual consumption (NAC) is plotted on the left vertical axis. Nominal electricity prices are plotted as bars and correspond to values on the right vertical axis.

- Changes in electricity consumption in the various groups of non-participants are quite revealing. Electricity usage of non-participants during the early years of the BPA program (pilot and 82-83 program) declined rather sharply over time. Rising prices are one factor that may help explain this trend. During this period, electricity prices increased sharply in the region (almost doubling between 1980 and 1984), although initial prices of less than 2¢/kWh were quite low (Figure 19). Moreover, much of the region was beset by an economic recession and high unemployment, which adversely affected purchasing power of some customers. In contrast, electricity consumption of non-participants during the later years of the program (1985 and 1986 Program) is steady over the three-year period, with a small increase observed in 1988. During this period, electricity price increases have been much more modest (in relative terms) and the regional economy has rebounded.
- It is clear that household electricity usage was declining in the early to mid-1980s in the region, irrespective of utility conservation programs. Thus, "net" savings attributable to BPA's program are much lower than gross savings. Since the mid-1980s, net and gross savings are comparable, as non-participant usage has remained steady over time. Data from the most recent years (1988) suggests that consumption might even be increasing slightly in the region (based on non-participant's usage), which may partially explain the observed increase in the 1988 electricity usage of 1986 program participants.

While it is not possible to draw definitive conclusions regarding the persistence of savings, these data from SCL and BPA do suggest that savings from these packages of building shell retrofits do not degrade significantly over the first six years after installation. In addition, data on persistence of savings highlight some fundamental methodological issues regarding interpretation of consumption patterns over time in participating and nonparticipating households. The potential for significant attrition in the original sample sizes of participant and non-participant households for various reasons (e.g., homeowner moves, other major changes to house such as remodelling) is a major evaluation problem. In the BPA studies, sample attrition was a problem, particularly in the non-participant group, in part because some of these households participated in the weatherization program at a later date. Keating (1991) reported that the sample size was reduced by about 30-35% reduction in the non-participants group over a three-year post-retrofit period in the 1985 and 1986 BPA program evaluations. One obvious question that arises is are there significant differences between remaining participants and non-participants compared to the original samples in terms of installed retrofits, first-year savings, etc. This further complicates the issue of assessing "net" savings over an extended time period.

Observation of several years of pre- and post-retrofit electricity consumption in the two groups does provide a broader picture of occupant behavior and other underlying factors that may affect consumption. However, it does not appear possible to unambiguously distinguish the effects of the "technical" improvement from occupant effects and responses to other factors when relying only on utility billing data and customer survey information. Another option might be to supplement this type of analysis with periodic short-term measurements of changes in thermal shell performance or equipment efficiency in order to develop a more robust estimate of the impact of technical improvements as distinct from occupant effects. This would help balance evaluation methods that focus primarily on determination of "net" savings with more attention on indicators that reflect the building energy performance of houses (e.g., space heat intensity).

7. PREDICTED VERSUS ACTUAL SAVINGS

About 20% of the retrofit projects in the BECA-B database included predictions of energy savings, based on methods ranging from simple engineering estimates (e.g., heat load calculations) to building energy simulation models such as HOTCAN or CIRA/EEDO. Tables 12 and 13 show predicted and metered savings for the space heat fuel, the type of retrofit project (e.g., R&D study, utility weatherization program), and the prediction method. Table 12 lists predicted savings for all end uses and Table 13 gives information for projects that predicted only space heat savings. Note that each retrofit project shown in the tables includes results that are averaged for a group of houses; the variance between predicted and metered savings for individual homes is considerably larger.

The basic inputs for engineering calculations or simplified audit tools used by some utilities include pre- and post-retrofit shell and glazing R-values, other important building characteristics (e.g., conditioned floor area, envelope surface and window areas, type of basement), and estimated infiltration rates. Combined with heating degree day information, this is enough for a simple prediction of energy savings using a $UA\Delta T$ calculation. Such methods (coded MHDD in Tables 12 and 13) are relatively straight-forward and were used by many utilities in their initial weatherization programs.[19] In some cases, the heating degree-day base was not fixed in the engineering heat loss calculations but rather the balance temperature was a variable that was determined to find the appropriate heating degree day base for each house (coded VHDD in Tables 12 and 13). Determining the balance temperature is generally done using pre-retrofit fuel consumption and thus requires normalizing fuel consumption records. Building energy simulation models, such as CIRA, often use this approach or a modified bin method (e.g., HOTCAN) and, also include algorithms that provide a more accurate energy balance (i.e., prediction method MONTH because an energy calculation of heating and cooling loads is typically performed for each month). For example, these models attempt to account explicitly for solar and internal gains, utilize more sophisticated algorithms to model infiltration and ground-coupling, and are designed so that predicted energy use can be calibrated to actual utility bills.

We believe that it is important to analyze results separately for R&D studies and utility programs because of differences in input data quality and, in some cases, model sophistication. In utility-sponsored programs, participants typically received a home energy audit prior to retrofit estimating energy savings from various measures. The predicted savings method (either an engineering heat loss calculation or a simplified building energy simulation model) is being evaluated under "normal" field conditions - a utility auditor that often only has access to previous utility bills (but not to detailed measurements). Moreover, in most program evaluations, utilities did not go back and re-adjust the auditor's predictions of savings if all recommended measures were not installed in a home.[20] This would explain a small portion of the variance between predicted and metered savings. More importantly, in some of the early pilot programs,

[19] The modified heating degree-day (MHDD) approaches typically fixed the balance temperature at a specified heating degree-day base (e.g., 65^{o}F or 60^{o}F) for all houses.

[20] We believe that typical practice was to take the auditor's initial estimate of savings from a utility energy audit database or the actual audit form and match it with that house's metered savings, and then compute program averages.

there is evidence that the audit methods systematically overestimated savings because they did not handle interactive effects among measures or because savings estimates (based on heat loss calculations) were not initially calibrated to the house's actual consumption level. In some cases, later programs effectively de-rated savings estimates to reflect over-estimated engineering predictions.

In contrast, analysts involved in R&D projects generally spent more time in obtaining accurate input data for their models, made predictions based only on installed measures, and typically used a sophisticated building energy simulation model (i.e., computer simulation that performed an energy balance for each month). For example, in evaluating the Manitoba Cut Home Energy Costs program (CHEC), the Energy and Mines department used audit information to model each house on HOTCAN, and then calibrated predicted energy use prior to retrofit to actual fuel usage and utility bills. Thus, in general, we would expect research studies to predict energy savings more accurately than large-scale utility programs.

The top section of Table 12 consists of savings predictions for packages of measures installed in weatherization programs by electric utilities in the Pacific Northwest. The bottom half of Table 12 presents results for gas-heated homes that installed various retrofit options (e.g., foundation insulation, new furnaces, house-doctoring) as part of R&D projects. Except for the Oak Ridge audit test conducted in New York, all of these studies used a modified degree day method (MHDD). With few exceptions, metered energy savings, on average, fell short of predictions in both the research studies and utility weatherization programs. Actual savings were within 20% of predicted estimates in only four of the 20 retrofit projects (see Figure 20). The actual reductions in the electricity consumption of groups of participating homes were typically 67% of predicted estimates in eight weatherization programs sponsored by electric utilities. The variance in results was quite large (i.e., ratio of actual to predicted savings ranged from 50-157% percent). The median value was 75% for 12 R&D projects that tested various retrofit options (foundation and wall insulation, house-doctoring) in gas-heated homes.

Coincidentally, the studies shown in Table 13 which predicted space heat (as opposed to NAC) savings tended to use the more sophisticated building energy simulation models. The median value in these 12 studies between actual and predicted estimates was within 15%. In contrast to Table 12, many of the studies predicting space heating use underestimated energy savings. However, we are unable to draw any substantive conclusions because the sample is small and the distribution is atypical - five data points are from the Manitoba Energy and Mines evaluation and three data points are from LBL's evaluation of the BPA Midway project.

Overall, based on this limited sample, it appears that there is substantial room for improvement in terms of the accuracy of model predictions. The agreement between model predictions and actual metered consumption is affected by the quality of the retrofit materials and installation, data available on building characteristics, weather, and occupant life-style, the varying skills of the input preparer, and the ability of the model algorithms to model physical processes and account for effects of occupant behavior. It is unlikely that even the most accurate predictive methods will be able to capture the effects of human behavior and thus we should always expect discrepancies between predicted and actual savings. We believe that a reasonable goal is that actual savings, averaged over a group of houses, should be within 20% of predicted estimates. These results also reinforce the importance of understanding and accounting for the effects of human behavior on retrofit performance and savings as well as the continuing need to actually measure energy consumption before and after retrofit. these limitations, Retrofit savings predictions are likely to continue to improve, as energy audit methods become more sophisticated and data on actual measured savings are fed back into the auditing and analysis process.

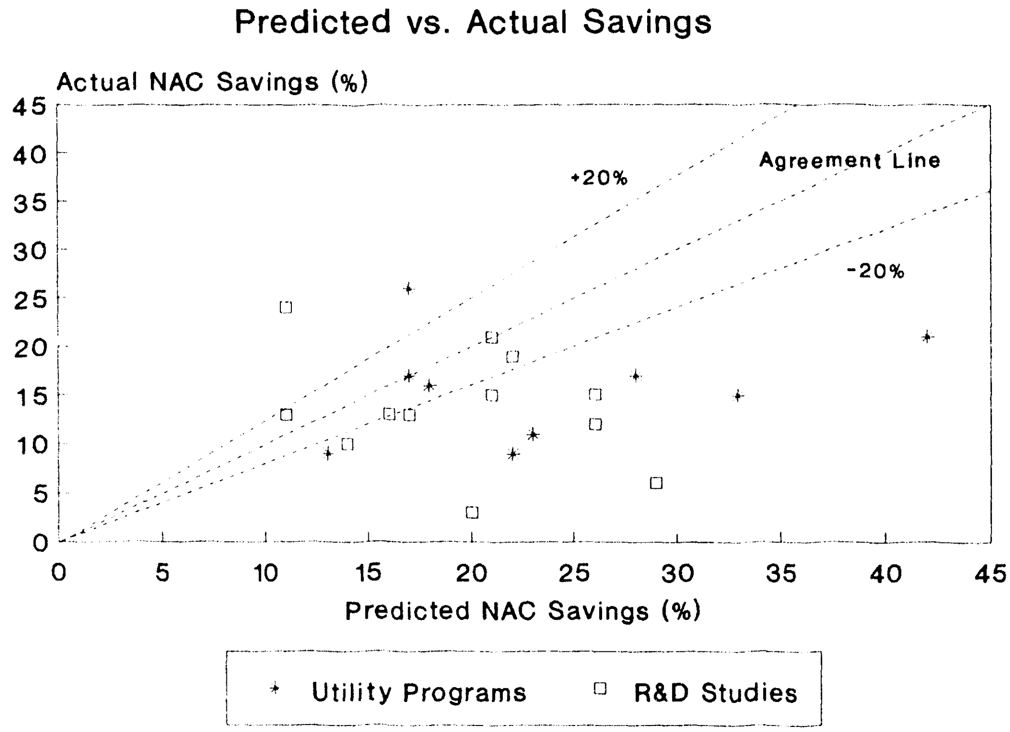


Figure 20. Comparison of measured vs. predicted energy savings for the 21 single-family retrofit projects shown in Table 12. Energy savings predictions are based on building energy audits and computer simulations. Projects are grouped by type of project (i.e., R&D study, utility weatherization program). The agreement line shows where metered savings equal predicted savings. Points below the agreement line correspond to larger predicted than actual savings.

Table 12. Predicted vs actual normalized annual consumption (NAC) savings.

Label	Sponsor Program	Program Type	# of Houses	Predicted NAC Savings	Actual NAC Savings	Predicted NAC Savings (%)	Actual NAC Savings (%)	Ratio of Actual/ Predicted	Prediction Method
	Electrically Heated Homes								
E006.1	80 Puget Power Pgm	U	6289	5450 kWh/yr	8580 kWh/yr	17	26	1.57	MHDD
E007.1	78 Portland General Electric Pgm	U	300	4080	3940	17	17	.96	MHDD
E009.1	79 Washington Water Power Pgm	U	1030	9870	4450	33	15	.45	MHDD
E011.1	81 Bonneville Power Administration Pilot	U	179	12000	6000	42	21	.50	MHDD
E016.1	80 Portland General Electric Pgm	U	208	4300	4040	18	16	.94	MHDD
E017.1	81 Idaho ZIP Pgm	U	101	3050	2180	13	9	.71	MHDD
E030.1	82 Bonneville Power Administration Pgm	U	229	7600	4800	28	17	.63	MHDD
E030.2	83 Bonneville Power Administration Pgm	U	248	5800	2900	23	11	.50	MHDD
E039.1	85 Bonneville Power Administration Pgm	U	252	5310	2356	22	9	.44	MHDD
	Median Electric Values (N=9)							.63	
	Gas Heated Homes								
G027.1	80 Pacific Gas & Electric House Doctor	R	13	14 MBtu/yr	16 MBtu/yr	11	13	1.14	MHDD
G028	78 Univ of Illinois Wall, Ceiling Insulation	R	12	20	42	11	24	2.08	MHDD
G029.1	82 Solar Energy Research Inst 50/50 Pgm	R	24	26	26	21	21	.99	MHDD
G051.1	84 MEO Interior Foundation Insulation	R	8	27	20	21	15	.73	MHDD
G051.2	84 MEO Exterior Foundation Insulation	R	5	16	11	14	10	.70	MHDD
G052.1	82 MEO Furn Replacement (Condensing)	R	3	37	33	22	19	.67	MHDD
G052.2	82 MEO Furn Replacement (Forced Draft)	R	13	24	19	17	13	.79	MHDD
G052.3	82 MEO Boiler Replacement (Forced Draft)	R	4	37	30	16	13	.81	MHDD
G052.4	82 MEO Wall Insulation	R	8	41	20	26	12	.49	MHDD
G067.1	89 Robinson Interior Foundation Insul	R	9	32	6	29	6	.20	MHDD
G067.2	89 Robinson Exterior Foundation Insul	R	6	17	2	20	3	.14	MHDD
G069.1	88 Oak Ridge NY Audit Test	R	32	35	20	26	15	.57	VHDD
	Median Gas Values (N=12)							.75	

U = Utility program; R = Research Study

MEO = Minneapolis Energy Office (now the Center for Energy and the Urban Environment); Robinson = Robinson Technical Services

MHDD = Modified heating degree day method; VHDD = Variable reference temperature degree day method

Table 13. Predicted vs actual space heat savings.

Label	Sponsor Program	Program Type	# of Houses	Predicted Space Heat Savings	Actual Space Heat Savings	Predicted Space Heat Savings (%)	Actual Space Heat Savings (%)	Ratio of Actual/ Predicted	Prediction Method
				Electrically Heated Homes					
E002	TVA Home Insulation Program	U	54	2170 kWh/yr	2210 kWh/yr	21	22	1.02	MHDD
E008.1	BPA/LBL Midway Project	R	5	840	1850	4	9	2.19	MONTH
E008.2	BPA/LBL Midway Project	R	5	4460	3240	23	16	.73	MONTH
E008.3	BPA/LBL Midway Project	R	4	6510	8200	33	42	1.26	MONTH
				Gas Heated Homes					
G064.5	ORNL/WECC WI Audit Test	R	20	20 MBtu/yr	16 MBtu/yr	19	16	.83	VHDD
				Mixed-Fuel Heated Homes					
M008.1	CSA/NBS Demonstration	R	142	59 MBtu/yr	45 MBtu/yr	40	31	.76	MHDD
M028.3	E&M Ceiling Insulation	R	47	17	21	-	-	1.14	MONTH
M028.4	E&M Wall Insulation	R	12	38	44	-	-	1.16	MONTH
M028.5	E&M Foundation Insulation	R	24	26	32	-	-	1.22	MONTH
M028.6	E&M Window Replacements	R	89	2	5	-	-	2.04	MONTH
M028.7	E&M Door Replacements	R	15	2	1	-	-	.41	MONTH
	Median Values (N=12)							1.15	

U = Utility program; R = Research Study

TVA = Tennessee Valley Authority; BPA = Bonneville Power Administration; LBL = Lawrence Berkeley Laboratory

NBS = National Bureau of Standards; ONRL = Oak Ridge National Laboratory; WECC = Wisconsin Energy Conservation Corporation

CSA = Community Services Administration; E&M = Energy and Mines (Manitoba)

MHDD = Modified heating degree day method; VHDD = Variable reference temperature degree day method

MONTH = Monthly-based computer simulation

8. CAPTURING FUTURE CONSERVATION POTENTIAL IN SINGLE-FAMILY HOMES

Some logical questions follow from analyzing these measured results for individual retrofit cases: To what extent can this experience be replicated elsewhere? How can these well-documented (but not statistically chosen) cases contribute to a more realistic estimate of the remaining conservation potential in the U.S. single-family stock? Thorough answers to these questions would require data on the building stock that are not yet publicly available, and would also be beyond the scope of this analysis. However, data presented in the preceding chapters provide several indicators of the opportunities that remain for retrofitting the single-family housing stock.

An earlier effort to extrapolate BECA results to a stockwide potential for multifamily retrofits produced an estimate of savings that ranged from 0.2 to 0.5 quads (1 quad = 10^{15} Btu), or 9-22% of total energy use in the multifamily sector (Goldman et al. 1988). The task of estimating multifamily savings potential posed fewer problems than a comparable estimate for the single-family stock because we were relatively confident that the stockwide saturation of measures, of the type documented in the BECA multifamily database, was relatively low. For retrofits in single-family homes, the situation is more complex. Some of the individual measures and retrofit packages described in this study are already present in the existing stock, to varying degrees. But data on the existing saturation of individual energy-saving features are still quite limited.

The best single data source on national stock characteristics is the Residential Energy Consumption Survey (RECS) conducted every three years by the U.S. DOE Energy Information Administration (EIA 1989). Although RECS is an important resource for many purposes, there are some significant gaps or limitations in the data collected up to now. For example, some important characteristics of heating equipment and distribution systems, such as equipment efficiencies, are not available. This is due in large part to the difficulty of gathering reliable technical data of this sort through surveys of household members. On-site energy audits for a sample of homes could be of great value in more accurately characterizing the physical features of the housing stock. Collaborative projects between EIA and the many utilities already involved in on-site energy audits offers one promising avenue.

Table 14 summarizes the data that are in RECS on energy-saving features of the single-family U.S. stock (EIA 1989). On a stockwide basis, there is still substantial potential for wall insulation and for adding insulation to partially-insulated attics. Upgraded glazing, despite its high cost, is a possibility in many homes--especially when remodeling or additions occur. Based on the RECS survey, there are substantial opportunities for adding all of the measures listed, for those single-family homes that are rented (about 15% of the total). Similarly, in milder climates there are significant numbers of single-family homes without basic envelope measures - despite the fact that the combination of cooling and heating energy savings may make these measures cost-effective. A final statistic of interest is the high percentage - nearly one in five - of recently-constructed, post-1980 homes (many located in the mild climates of the South and West) that still lack basic energy-saving features like full attic and wall insulation, caulking, and weatherstripping.

Table 14. Energy-efficiency features in the U.S. single-family stock (1987).

Measure	Percent of Single-Family Housing Units							
		By Occupancy		By Climate Zone (HDD, base 65° F)				Built 1980 or Later
	Stock Avg	Owner Occup.	Rented	>7000	5500-7000	4000-5500	<4000	
(millions of houses)	(60.5)	(51.6)	(8.9)	(6.2)	(16.7)	(14.6)	(22.9)	(7.0)
Caulking or weatherstripping	74	78	52	81	79	79	66	81
Partial or full attic insul.	82	87	49	92	84	81	76	91
(Full attic insul.)	68	74	35	76	69	73	63	81
Partial or full wall insul.	59	64	28	82	66	58	48	79
(Full wall insul.)	50	55	23	71	55	49	41	76
Storm windows or "insul. glass"								
- on all windows	52	55	35	--	--	--	--	--
- on < 50% of windows	36	32	55	--	--	--	--	--

Source: EIA, "Residential Energy Consumption Survey: 1987 Housing Characteristics."

These national statistics are reinforced by other indicators from studies cited in the BECA data base. After many years of aggressive state- and utility-sponsored retrofit programs in the Northwest, for example, regional estimates are that only about one-half of the potential for cost-effective retrofits of single-family, all-electric homes has been accomplished. For the nation-wide low-income weatherization program, DOE estimates that approximately 80% of eligible low-income households have not yet been served by the program (some of these, of course, have been or will be reached through other state or utility retrofit programs, or retrofitted independently by building owners).

Equally significant are the indicators of what might still be done in those homes that have already received some basic retrofit measures. For example, the BECA data can be compared not only in terms of energy savings, but in terms of energy intensity after retrofit - with each other and with the single-family stock as a whole. Figure 8 shows that the range of space heating intensities (heating fuel use per square foot per heating-degree-day) after retrofit in low-income weatherization programs was about 12-20 Btu/ft^2-HDD. This is still at or above the average for all gas-heated households, from RECS, and considerably higher than the "best-practice" energy intensity after retrofit, averaging 8.2 Btu/ft^2-HDD, for the Minnesota M-200 program discussed earlier. Several other state-of-the-art weatherization programs, in Minnesota, New York, and Michigan, achieved post-retrofit energy intensities averaging about 11 Btu/sq.ft.-HDD, as did the CSA "optimal retrofit" demonstration project, combining shell and system retrofit measures, over a decade ago (see Table 4). There is an equally dramatic range in post-retrofit energy intensities for all-electric homes, between typical and best-practice cases. Table 10, comparing several all-electric retrofit programs in the Northwest, gives a median post-retrofit value across all programs of 4.2 Btu/ft^2-HDD. This is higher than the estimated stock average of about 3.5 for the entire

U.S., and considerably higher than the best program in the region (the Hood River demonstration, discussed earlier) with an average post-retrofit intensity of 2.6 Btu/ft^2-HDD. These post-retrofit values suggest that, even in homes already retrofitted with conventional measures, there are probably opportunities for additional savings, and that in those remaining to be retrofitted we face a range of options on how aggressively to intervene.

Neither RECS data nor other sources can tell us much about the cases where significant, short-payback retrofit opportunities still exist for other commonly available, widely cost-effective measures such as compact fluorescents, solar shading on exposed windows, and efficient appliance replacements. However, the percent of homes with attic and wall insulation, as shown in Table 14, are undoubtedly much higher than those with improved lighting and window treatments. Of equal interest is the potential for less familiar technical measures: sealing of leaky air-distribution ducts, strategic landscaping to reduce cooling and heating energy, and reduction of peak electric demand through HVAC and appliance controls or residential thermal storage. There are also options for major efficiency gains in equipment that may be present in only a fraction of the stock, but represents a major energy use where it does occur. Examples include home well-pumps, spas, and swimming pools.

In the longer term, there are many other promising technologies that can create new options for residential retrofits. For example, "super-windows" with advanced optical and thermal coatings may soon offer new options for replacing old windows to obtain both energy and comfort benefits far beyond those available with conventional double-glazed replacements. As new technologies such as these continue to develop, it will be important to assess their actual performance, and to reliably communicate both successes and failures to the broader circle of potential users. That is a role for continuing efforts in data compilation and analysis, building upon and complementing the field measurement activities of our many colleagues.

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10. ACKNOWLEDGEMENTS

We wish to express our appreciation to Dr. Fred Abel and John Millhone of the Department of Energy for their long-term support of the BECA project. We also thank the large network of researchers and program staff that contributed retrofit data to the BECA database. In particular, Kathy Greely, Ed Haber, Nick Hall, Martha Hewett, Bob Hough, Larry Kinney, Ken Klassen, Bob Lordo, Maureen Quaid, John Randolph (of the Virginia Center for Coal and Energy Research, not LBL), Dave Robinson, and Patti Witte made exceptional efforts to respond to our requests and provide additional information. Jeff Schlegel provided us with extensive comments on an earlier abridged version of this paper published in the 1990 ACEEE proceedings. We also thank Darrell Beschen, Margaret Fels, Kathy Greely, Eric Hirst, Ken Keating, Jon Koomey, Alan Meier, Debra Okumo, Kathy Reynolds, Lester Shen, and Arun Vohra (DOE) for their helpful review comments on a draft of this report. John Randolph provided, as always, invaluable assistance in office management and report preparation.

A number of the retrofit projects described in this study were funded by the Department of Energy under the Existing Buildings Retrofit Research Program, managed by Oak Ridge National Laboratory.

The work described in this paper was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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