Measured Energy Savings and Economics of Low-Income Weatherization Progress

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This paper compares measured results from evaluations of low-income weatherization programs in five categories: statewide programs, state pilots, programs targeting high users, utility-sponsored programs, and mobile-home weatherization programs. Statewide weatherization programs in northern states achieved normalized annual consumption (NAC) savings of 8-18%. Pilot programs achieved significant increases in cost-effectiveness over existing statewide programs. Utility-sponsored programs tended to be less cost-effective than state programs, though recent utility program evaluations in Wisconsin and New York report NAC savings of 18% and 23%, respectively and high cost-effectiveness. Programs targeting high users achieved 21-25% NAC savings. Results from the more successful programs indicate that blower door-guided infiltration reduction and high-density wall insulation produce large, cost-effective savings. Recent work has shown that mobile-home weatherization can achieve comparable savings if measures specifically designed for mobile homes are applied. Periodic evaluations are important to refining program design, since not all evaluation results can be generically applied.

Introduction

The complexity of low-income weatherization has increased dramatically in the last ten years, as documented by Schlegel et al. (1990). In the early years of federally sponsored weatherization, the standard measures included ceiling insulation, caulking and weatherstripping, and storm windows. Since the early 1980s, the list of traditional shell measures has been expanded in both federally sponsored and utility-sponsored programs. New retrofit measures include heating system retrofits and replacements, blown-in wall insulation, and water-heating retrofits. Additionally, the per-house expenditure limit has been raised. New diagnostic tools, including blower doors and infrared cameras, are used by many weatherization agencies. Better training of crews and auditors and client education are now an integral part of many weatherization services. Some programs target high users, and innovative strategies have been developed for mobile homes. Weatherization programs around the country have adopted these new measures and strategies in different configurations and to varying degrees.

Now that program designers have a larger menu of retrofit measures and diagnostic tools to choose from, one would expect a greater divergence in individual program results. To ascertain which methods have proved to be most successful, this paper compares evaluation results from statewide programs, state pilots, programs targeting high users, utility-sponsored programs, and mobile-home weatherization programs.

Methodology

This study reports on the single-family component of the Buildings Energy Use Compilation and Analysis (BECA) database at Lawrence Berkeley Laboratory. The BECA database is a compilation of measured data on the performance and cost-effectiveness of energy-saving measures in new and existing buildings. Information for the database is gathered from a variety of sources: conference proceedings, journals, and contacts with program managers and researchers. Data on weather-normalized energy consumption, building characteristics, and retrofit measures and costs are used to compare results from different retrofit measures and delivery techniques.

Not all the studies included in the database had control groups. Consequently, we opted to present gross rather than net savings, but the available data have been screened to help assure that savings are related to the actual retrofit, not external factors. Typical screening criteria include no supplemental heating fuels, no occupancy changes, and continuous billing histories. PRISM is the most common weather-normalization method. We generally report only screened energy consumption data. The original researchers used different statistical criteria to screen data, but an $R^2 > 0.7$ or 0.8 and a coefficient of variation < 0.1 were common. Some projects with measured savings were excluded from the database due to problems with data quality, completeness, or comparability.

The main economic indicator used for comparative analysis is the cost of conserved energy (CCE), which is calculated using a 7% real discount rate. A retrofit is cost-effective if the cost to conserve the energy is less than the relevant energy cost. The CCE is calculated as follows:

$$CCE = \frac{RC * CRF + \Delta OMC}{\Delta E} \tag{1}$$

where:

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

RC = Retrofit cost (in current dollars)
ΔOMC = increase in first-year operation and maintenance costs
ΔE = annual energy savings
d = discount rate
n = lifetime of measures

Regional avoided costs and retail rates vary, but, for comparison, typical residential rates for natural gas are approximately $6/MBtu. Lifetimes of either 15 or 20 years were assumed for the packages of weatherization measures. Programs that spent most of their funds on ceiling and wall insulation were assigned a 20-year lifetime. Programs that included many shorter-lived measures, such as caulking and weatherstripping, and equipment tuneups, received a 15-year lifetime. All costs reported in this paper are in 1991 dollars. For more detail on methodology and results, refer to Cohen, Goldman, and Harris (1991).

Results

Low-income weatherization is primarily funded by money from the federal government and utilities. The primary source of data on the energy savings and cost-effectiveness of low-income weatherization programs are evaluations of state and utility programs. Program evaluations tend to be infrequent, and many programs have never been evaluated. This section presents results from statewide programs, state pilots, programs targeting high users, utility-sponsored programs, and mobile-home weatherization programs. Tables 1 and 2 summarize data from these evaluations. Figure 1 compares cost-effectiveness and energy savings results for the various types of programs. Energy savings and economics for each of the five program categories are discussed below.

Statewide Programs

A national evaluation of low-income weatherization activity in 1981 found normalized annual consumption (NAC) savings of 10% (Peabody 1984) and a cost of conserved energy (CCE) of $11.90/MBtu (1991$). Only seven states have evaluated their weatherization programs since 1980: six northern states--Wisconsin, Michigan, Minnesota, Ohio, New York, and Illinois--and Virginia. (Other states have conducted evaluations, but the results did not meet the minimum data requirements for the BECA database. Iowa, Maryland, and Pennsylvania are currently conducting evaluations, and Oak Ridge National Laboratory is conducting a national low-income weatherization evaluation.) The 12 studies clustered in northern states, found that the NAC of the retrofitted homes decreased by 8-18%, while savings ranged from 9-29 MBtu/year. Cost-effectiveness results for these programs were mixed. CCEs ranged from $5.60-$14.30/MBtu, with a median of $6.80/MBtu. For the more recent evaluations, the CCEs tend to be clustered at the low end of this range ($5-9/MBtu), with the exception of the 1985 Ohio study (see Table 1). Compared to the other programs, Ohio did not emphasize insulation measures. An 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). The process and results of these statewide program evaluations have led to significant improvements in the delivery and performance of low-income weatherization programs in these states and others with similar climates. Ohio, in particular, has dramatically increased savings and improved cost-effectiveness. Undoubtedly, performance is poorer in most states that have not conducted evaluations to improve their programs.

The 1988 Virginia evaluation is the only recent evaluation of a weatherization program in a relatively mild climate. Retrofit measures included intensive caulking and weatherstripping, attic insulation, storm windows, and replacement windows. The program achieved average NAC savings of only 7 MBtu/year (7%) and the CCE exceeded $17/MBtu (Randolph, Greely, and Hill 1991). Savings in these Virginia homes were significantly lower than those reported for houses in colder climates. Since retrofit costs in Virginia were comparable to those in other states, CCEs were much higher in the Virginia program (see Figure 1). 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

Table 1. Low-Income Weatherization Programs

Year/State	HDD (65°F)	No. of Houses	Retrofit Measures[a]	Normalized Annual Consumption (NAC) Preetro. (MBtu)	Average Savings (MBtu)	(%)	Space Heating Intensity Before	After (Btu/ft²-HDD₆₅)	Retro. Cost (91$)	Simple Payback (Years)	CCE (1991$/ MBtu)
Post-1980 State Program Evaluations											
1981 National		965	IA,IW,IP,WM,CW,DR	133	14	10			1490	13	11.90
1981 WI	7600	11	CW,IA,WH,IS	144	21	14	17.6	14.6	2400	16	12.80
1981 MN	8000	239	CW,IA,WH,DR,WM,IP,IW	161	23	14	19.2	16.4	1200	7	5.70
1982 WI	7600	243	CW,IA,WM,IS,DR,IP,ID	124	13	10	12.5	11.2	1680	18	14.30
1983 MI	6700	364	CW,IA,WM	182	21	12	24.2	20.7	1180	7	6.10
1984 MN	8000	155	CW,IA,WM,IW,IP	128	12	9	14.0	12.7	1350	17	10.70
1984 IL	6100	497	CW,IA,WM,T,IW,IP	188	14	8			960	10	7.40
1984 MI	6700	155	CW,WM,IA	177	17	10	22.4	19.7	1140	9	7.40
1985 OH	6000	1083	WH,CW,IS,ID,IA	153	18	11	15.7	13.4	2160	18	14.00
1986 MI	6700	65	CW,WH,WM,IA,IS	172	23	13	16.3	14.2	1160	10	5.60
1988 NY	7000	683	PI,WH,IA,IW	156	19	12	13.1	11.4	1070	9	6.10
1988 IL	6100	192	PI,RD,IA,WR,IW,IF,WM,IS	179	21	12	14.1	11.8	1110	10	5.60
1988 VA	4300	91	CW,IA,WM,RD,WH,WR	104	7	7	19.6	17.3	1090	26	17.40
1988 OH	6000	660	PI,IA,IW	157	29	18	17.3	13.4	1880	11	6.20
State Demonstration Programs											
1986 MI	6700	173	CW,IW,IA,WH,WM,T	172	31	18	16.3	13.2	1100	7	3.40
1988 MN M200	8000	128	IA,IW,IS,CW,T,IP	142	25	18	10.5	8.2	1440	11	6.30
1989 VA Pilot	4300	43	PI,WH,IA,IW,SD,RD,HS	153	24	16	21.0	15.7	1060	6	4.80
State Pilot Programs Targeting High Users											
1985 MN Project Choice	8000	30	PI	247	21	9	15.5	14.1	720	5	4.90
1985 MN Project Choice	8000	13	PI,IA,IW	229	48	21	14.3	11.3	2710	9	6.20
1984 MI HRW	6600	41	CW,WH,IW,IA,HR,HS	388	95	25	30.7	21.9	4360	6	4.30
1985 MI HRW	6600	158	CW,WH,IW,HS,IA,HR	376	81	21	32.2	24.8	4160	7	4.80
1988 OH Warm Choice	6000	148	PI,IA,IW,TU,CF	150	34	23	16.7	12.0	2460	13	6.80
Utility Programs											
1983 WI Utilities	7500	606	CW,IA,HS,IW,HR,IS	149	29	19	12.4	10.0	2770	11	10.80
1984 WI Utilities	7500	483	IA,WP,IP,HR,WH,WM,IF,CW	139	23	17	11.7	9.7	1980	11	9.40
1986 CA PG&E	2700	5920	IA,CW,ID	69	5	8			620	21	13.50
1987 WI Utilities	7500	195	IA,IW,CW	184	42	23			1870	7	4.20
1987 OH Utilities	6000	8912	CW,WM,IA	135	12	9	15.4	13.6	580	10	5.30
1990 NY Niagara Mohawk	6900	47	IA,IW,PI	173	30	18	14.9	11.9	1480	8	4.60

(a) See key following Table 2.

Table 2. Mobile-Home Retrofits

Year/Project	HDD (65°F)	No. of Houses	Retrofit Measures	Normalized Annual Consumption (NAC) Preretro. (MBtu)	Average Energy Savings (MBtu)	(%)	Retro. Cost (91$)	Simple Payback (Years)	CCE (1991$/MBtu)
1981 MN LIW	8000	35	HS,IA,IF	122	13	10	980	11	8.40
1984 MN LIW	8000	28	CW,IA,WM	117	3	3	1030	45	33.00
1984 MI LIW	6700	47	CW,WM	98	4	4	440	15	16.00
1986 IHWAP	6100	227	WR,IF,T	86	6	6	1250	36	21.00
1986 COAD	6000	99	CW,SK,RD,WH,HS,WM	70	2	3	940	41	61.00
1986 CA LIW (PG&E)	2700	671	IA,CW,ID	52	0.6	1	490	145	89.00
1987 OH LIW	6000	60	CW,WM	67	2	3	370	40	22.00
1989 VA LIW Pilot	4300	12	PI,WR,RD,WH,IF		11		670	9	6.70
1989 NREL	6000	14	PI,IA,IF,WM	93	22	24	1500	11	6.40

KEY FOR TABLES 1 AND 2

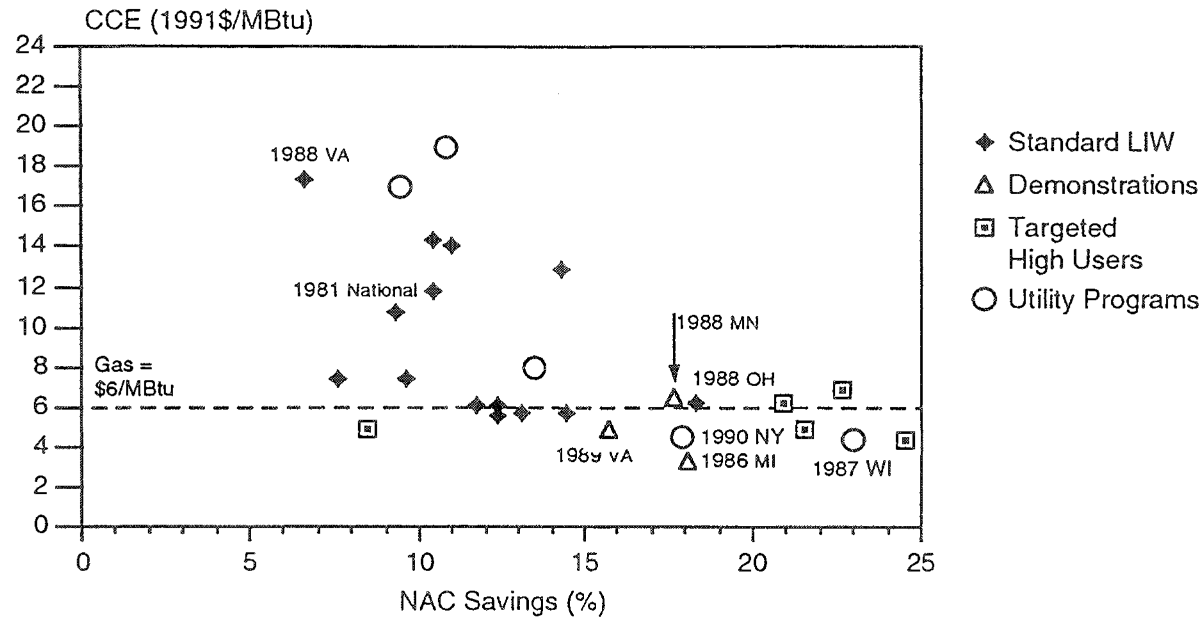
Retrofit Measures (listed only listed if they were installed in 20% or more of the sample).

CF	Condensing furnace replacement
CW	Caulking/weatherstripping
DR	Storm doors
HS	Heating system retrofit
IA	Attic insulation
ID	Duct insulation
IF	Subfloor insulation
IP	Foundation insulation
IS	Sill box insulation
IW	Wall insulation
IX	Misc. shell insulation
PI	Pressurization, infiltration reduction
RD	Replace doors
SK	Mobile home skirting
T	Clock thermostat
TU	Furnace cleaning and tuning
WH	Water-heating retrofit
WM	Storm windows
WR	Window replacement

Normalized Annual Consumption (NAC) pre-retrofit = weather-normalized annual consumption of space heat fuel prior to retrofit.

Retrofit Cost = materials and labor, but not program overhead.

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



For post-1980 state evaluations shown in Table 1, the average cost of conserved energy (CCE) is plotted against percentage savings of the space heat fuel (NAC, or normalized annual consumption). The 27 data points represent results from over 13,000 homes. The dashed line represents the average U.S. residential price for natural gas. The most successful programs are below the dashed 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.

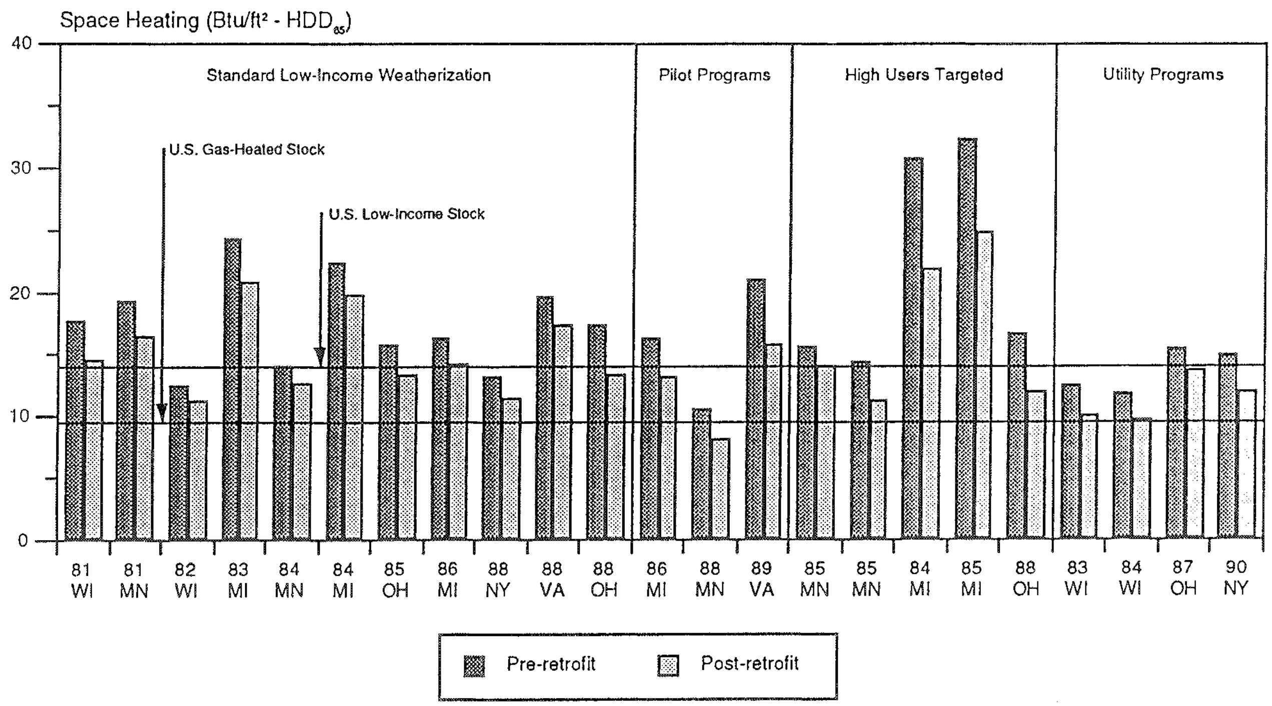
Figure 1. Results from Post-1980 State LIW Programs

benchmark for estimating performance in mild-climate states that have not conducted evaluations. Nonetheless, the lack of measured data from states in milder regions is a serious gap in our ability to assess low-income weatherization performance.

Space heating energy use (and the savings potential) is strongly affected by the severity of the climate and the size of homes. One way to capture and account for these factors across programs is to calculate space heating intensities before and after weatherization (see Figure 2). We define the space heating intensity index as heating energy consumption (in Btus) per square foot of heated floor area per heating degree day (HDD, base 65°F). As shown in Figure 2, 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 heating intensity of Michigan homes is approximately 20 Btu/ft^2-HDD, compared to 11-16 Btu/ft^2-HDD for low-income homes in the other northern 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 substantially lower than the estimate of 13.6 Btu/ft^2-HDD for U.S. low-income housing stock (Energy Information Administration 1989). Historically, heating energy usage in low-income homes has significantly exceeded stock averages, as shown in Figure 2. While space heating intensity is a useful standard for comparison, these results should be interpreted cautiously, with allowance for data limitations, inconsistencies, and other uncertainties.

State Pilot Programs

The three state demonstration projects in our database (see Table 1) show encouraging results and offer well-documented improvements in energy savings and cost-effectiveness. The 1988 Minnesota M200 project and the 1986 Michigan low-income weatherization pilot offer insights into optimal retrofit strategies in cold climates. The 1989 Virginia pilot suggests that large savings and cost-effectiveness can also be achieved in milder climates (4,300 HDD_{65} in this case). Measures and results for these



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 1.) For comparison, we show an 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 (Energy Information Administration 1989).

Figure 2. Low-Income Weatherization Space Heating Intensities

three programs are discussed here briefly. Recommendations based on these programs are included in the Recommendations section of this paper.

The saturations of blown-in wall insulation and clock thermostat retrofits were increased in all three demonstration programs, as compared to earlier state programs. Storm window installations were reduced or eliminated entirely. Blower doors were used to locate and seal bypasses in the Minnesota and Virginia programs, but not in Michigan. 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. These three pilot programs achieved an average of 16-18% NAC savings, compared to 7-13% for the predecessor programs (see Table 1). All three demonstration programs were significantly more cost-effective than the original programs. The CCEs ranged from $3.40-$6.30/MBtu for the pilot programs, versus CCEs of $6-17/MBtu in the corresponding earlier state programs. For Minnesota and Michigan, which were already running relatively sophisticated programs, cost-effectiveness increased by a factor of 1.7. Virginia started with a basic weatherization program and was able to improve cost-effectiveness by a factor of 3.6.

The success of these three programs should be repeatable on a larger scale. Indeed, superior results are likely because larger-scale programs could surmount the idiosyncracies of the pilot programs. In the Minnesota M200 program, preretrofit space heating intensities were already low (see Figure 2), and in Virginia the weatherization crews had only two weeks of training in the new procedures and in many cases installed measures not called for by the new protocol.

Programs That Target High Users

Some programs target high users because these clients typically have both utility bill arrearages and the potential for large and cost-effective energy savings. Table 1 shows results for five programs that targeted high users. With the exception of one program that conducted only infiltration reduction work, NAC savings ranged from 21-25%; in comparison, state weatherization programs in northern states saved 8-18% of the NAC. Expenditures for the four comprehensive high-user programs far exceeded those for the state programs: $2,700-$4,400 versus $1,000-$2,400. CCEs for the programs targeting high users ranged from $4.90-$6.80/MBtu. Programs targeting high users can obtain large-scale, cost-effective savings, but consideration must also be given to equity issues when selecting weatherization recipients. As Figure 2 shows, some of these programs targeted high users more effectively than others. The two sets of Michigan homes had space heating intensities twice that of most other weatherization studies documented in this paper.

Utility-Sponsored Programs

Utility-sponsored programs install many of the same measures as federally funded programs, but expenditures vary from $600-2,800 per house (total costs including any funds from other sources). The more comprehensive programs install heating and water-heating retrofits in addition to shell measures, such as attic insulation. Table 1 summarizes results from six utility program evaluations. Five of the six studies were conducted in cold climates (Wisconsin, Ohio, and New York). The 1983 and 1984 Wisconsin programs offered a wide range of retrofit measures, including both heating system replacements and shell retrofits. NAC savings were large (17-19%), but costs were high ($1,980-2,770 per house), and the CCEs in the two studies averaged $9.40/MBtu and $10.50/MBtu. In the Ohio and California studies, only three retrofits were installed in most homes: caulking and weatherstripping, attic insulation, and either duct insulation (California) or storm windows (Ohio). NAC savings were much lower than in the Wisconsin studies: only 5 MBtu/year in California and 12 MBtu/year in Ohio. The California program was not cost-effective, with a CCE of $13.50/MBtu. In the Ohio program, volunteers provided significant labor and thus the CCE of $5.30/MBtu is not comparable to figures from other studies. The 1987 Wisconsin program and the 1990 New York programs concentrated on ceiling and high-density wall insulation and infiltration reduction. NAC savings were 18% and 23%, with CCEs less than $5/MBtu. Lessons from the most refined and cost-effective state weatherization programs should be incorporated in utility programs, as has been done in Wisconsin and New York to increase cost-effectiveness.

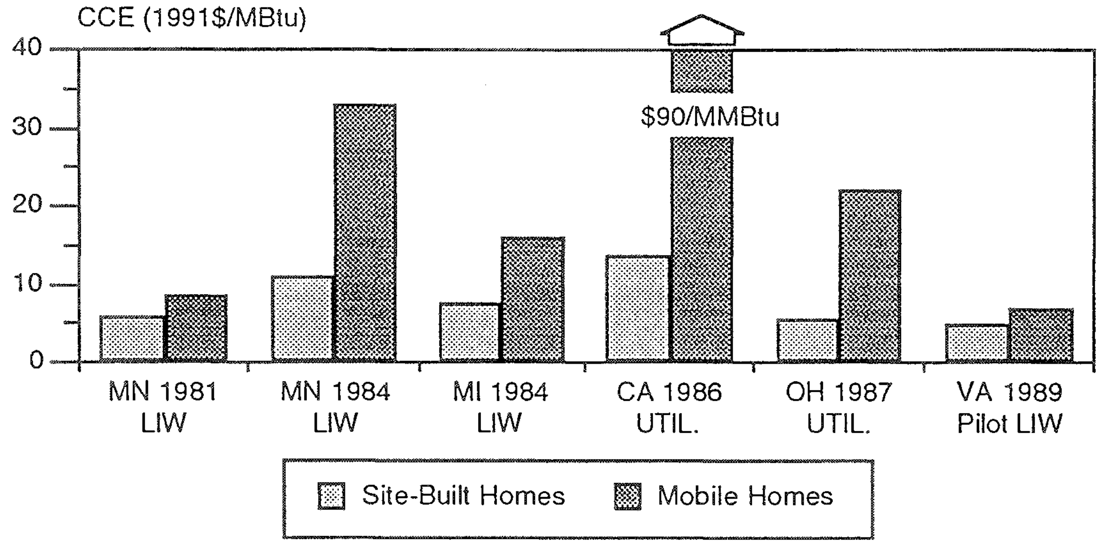
Mobile Home Weatherization

Fewer than 1.5% of the retrofitted homes for which we were able to find data are mobile homes, although mobile homes constitute 7.8% of the detached single-family housing stock (Energy Information Administration 1989). Moreover, mobile homes account for about 10% of the single-family homes eligible for federal low-income weatherization funds (personal communication, D. Beschen, U.S. DOE 1991).

At present, most programs that weatherize manufactured homes attempt to use the same retrofit techniques as for site-built homes; few have developed specialized techniques adapted to manufactured housing materials and construction practices. Consequently, average weatherization savings tend to be much lower for mobile homes than for site-built homes, while retrofit costs are comparable. For the six low-income weatherization programs for which we had enough information to compare results of weatherizing site-built and mobile homes, retrofitting site-built homes was more cost-effective in all cases (see Figure 3).

With the exception of the 1981 Minnesota study, the 1989 Virginia pilot, and the National Renewable Energy Laboratory (NREL) study, average CCEs for retrofitting manufactured homes exceed $10/MBtu. Among the nine mobile home studies in our database, it appears that only these three installed significantly different retrofit measures in manufactured homes than in site-built homes. In the 1981 Minnesota program, the manufactured homes received more furnace work and floor insulation than the site-built homes. In the 1989 Virginia pilot, extensive sealing and duct work was performed using blower doors; large leaks in the duct work and disconnected sections were found to be common.

The most recent data on mobile home weatherization is from the National Renewable Energy Laboratory (formerly SERI). Researchers at NREL have developed a weatherization protocol specifically for mobile homes, and it has been adopted by Colorado's LIW program. The protocol specifies roof blow, belly blow, blower door-guided air sealing and duct repair, interior storm windows, and furnace tuneups. Other obvious repairs are made when necessary, and not all retrofits are applicable or necessary for each home. In order to determine the effectiveness of the new weatherization protocol under typical field conditions, 67 owner-occupied homes were selected for evaluation from a list of mobile homes



Cost-effectiveness of the six programs for which we had sufficient data to compare retrofits of site-built and mobile homes.

Figure 3. Comparative Cost-Effectiveness of Weatherizing Site-Built and Mobile Homes

weatherized in 1989-1990. The houses were selected after the work was finished in order to avoid the possibility of more care being used in weatherization of the evaluation sample. The final screened sample consisted of 14 homes, which averaged savings of 22 MBtu/year (24% of the NAC) and a CCE of $6.40/MBtu. The NREL study shows that mobile homes can achieve large savings and cost-effectiveness under typical field conditions if measures specifically designed for mobile homes are used.

In contrast, applying site-built measures to mobile homes results in small savings and is not cost-effective (see Figure 4). Applying the most relevant site-built retrofit measures (as in the 1981 Minnesota program) increases cost-effectiveness and savings, but applying measures specifically designed for mobile homes results in larger savings and improved cost-effectiveness.

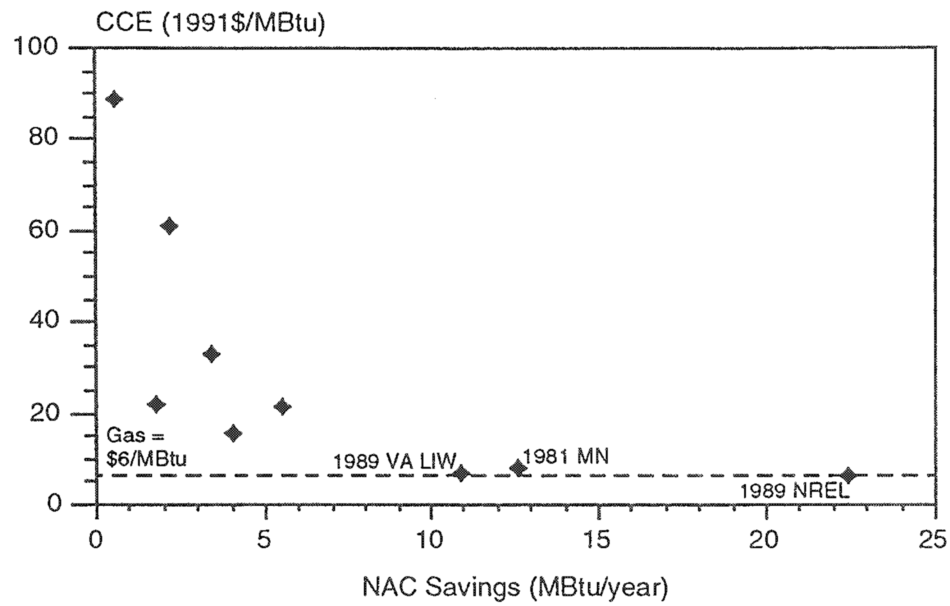
Recommendations

Our recommendations are based on lessons from the more successful low-income weatherization programs. These programmatic and technical recommendations draw upon the M200 Enhanced Low-Income Weatherization Demonstration Project (Shen et al. 1990) from Minnesota, lessons from evaluations of the Michigan (Kushler and Witte 1988) and New York weatherization programs (Kinney, Bretschneider, and Baldwin 1990), and Schlegel et al. (1990). We include a list of general guidelines and recommendations that program administrators and evaluators felt contributed to the particular success of their programs.

Program Design and Implementation Recommendations

Energy saved and cost-effectiveness, rather than units weatherized, should be the primary performance indicators for weatherization programs. Programs whose goals are to weatherize the largest possible number of homes tend to install capital-intensive measures--in order to quickly reach the expenditure limit and move on to the next house--while neglecting cost-effective, labor-intensive retrofits, such as blower door-guided infiltration reduction and wall insulation.

Weatherization programs that install the exact same package of measures (or spend the same amount) in all homes are likely to produce suboptimal results. To the extent possible, weatherization programs should target homes that are high energy users or, at least, should spend more money in these homes. These homes are likely to have the largest savings potential and afford maximum benefits for dollars invested. However, concern also needs to be given to equity, not just efficiency, when selecting weatherization clients.



For the mobile-home weatherization evaluations shown in Table 2, the average cost of conserved energy (CCE) is plotted against the savings of the space heat fuel (NAC, or normalized annual consumption). The dashed line represents the average U.S. residential price for natural gas. The most successful programs are near or below the dashed 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.

Figure 4. Results of Mobile-Home Retrofits

Weatherization auditors need to be given the flexibility, training, and resources necessary to do a proper job. Auditors should have records of all fuel use for a house divided into baseload and weather-sensitive components so that after inspecting the house and interviewing the clients, they can estimate space heating intensity and water-heating use. Energy use data, a visual inspection of the house, and some simple measurements (conditioned area, a blower-door test, and a furnace inspection) are sufficient 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 changes.

For heating system retrofits, consideration should be given to allotting some money for maintenance work. Operation and Maintenance (O&M) activities such as changing filters and biennial cleaning and tuning will help ensure continued savings at minimal cost, allow for safety checks, and provide opportunities to reinforce clients' energy awareness.

Weatherization programs should correct existing hazards and not cause any new ones. Furnaces should be inspected for safety problems, such as blocked flues, improper venting, and 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 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 clients, who 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.

Technical Recommendations

The following technical recommendations are drawn from successful programs as well as other studies of individual retrofit measures. 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: the optimal set of weatherization measures depends 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 cost-effectiveness cutoff 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 find only the most obvious air leaks, though some successful programs, such as Michigan's, do not use blower doors.

High-density blown wall insulation produces significant savings and can be highly cost-effective in cold climates when installed by properly trained crews. The two standard and pilot programs that achieved the largest savings also installed the highest saturations of wall insulation (18% NAC savings with 60% of the homes receiving wall insulation). Insulating walls with high-density materials often reduces infiltration so that further airsealing is unnecessary.

High-efficiency condensing furnaces are cost-effective to install in cold climates if existing furnaces are near the end of their useful life. Even in retrofit applications (as opposed to replacements), the economics of condensing furnaces have improved as installed costs have been reduced (e.g., as low as $1,500-$1,700 in Wisconsin). As costs have fallen, some state programs have placed 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. See Cohen, Goldman, and Harris (1990) for more detail on the performance of individual retrofit measures.

Additional attic insulation is a relatively low-cost measure that produces substantial savings. It is a cost-effective retrofit, even in fairly mild climates or in homes with 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 replacement doors and windows are expensive retrofits that save little energy, although their nonenergy benefits are attractive to occupants. If the primary concern is cost-effectiveness, weatherization funds should be spent on other more cost-effective measures. 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 per year at an average cost of more than $3,600 per house (Hill 1990).

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 are demonstrated "winners." Additional retrofit options will surely emerge as cost-effective strategies, with increased emphasis on monitoring and evaluation.

Conclusions

Recent evaluations in northern states prove that refined weatherization techniques allow for cost-effective programs that can save 15-20% of total energy use. However, little evaluation has been done in most areas of the country, and weatherization in these areas is undoubtedly not as cost-effective. Ongoing evaluations are needed to establish a benchmark for performance and to revise program designs for greater effectiveness. Much of the knowledge from the more advanced programs is directly transferable. A key challenge for low-income weatherization is to transfer and adapt lessons from state-of-the-art programs to regions that are lagging behind current best practice. In addition, specialized mobile-home weatherization techniques should be adopted by weatherization agencies in all regions.

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