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Energy savings and economics of retrofitting single-family buildings

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Abstract

This study assesses the energy savings and cost-effectiveness of individual retrofit options and packages of measures in single-family buildings, based on analysis of metered energy consumption and actual installation costs. We present results for 14 individual shell, heating system, and water heating measures, as well as 21 electric utility weatherization programs. The data on individual retrofit measures represent 32 retrofit projects, ranging in size from three to 30 000 houses. Most of the retrofitted homes are located in cold climates in the United States and use natural gas for space heating. Installation of additional ceiling and wall insulation was quite cost-effective, with normalized annual consumption (NAC) savings ranging between 12–21% in 10 retrofit projects, and average cost of conserved energy (CCE) values between $1.60–6.50/GJ. Retrofit technique (interior vs. exterior insulation) and basement condition (unconditioned vs. conditioned) strongly influenced the level of energy savings in homes that installed foundation insulation, although payback times were generally quite long. Window replacements were found to have small NAC savings (2–5%) and were not cost-effective (CCE > $15/GJ). Flame retention burners for oil furnaces produced significant savings (19–34 GJ/year for the three studies in our data base) and had CCEs of less than $2.70/GJ. Several retrofit strategies that improve the efficiency of gas furnaces produced annual savings of 7–20 GJ/year (4–14% of the NAC), with CCEs that were comparable to current gas prices ($5–7GJ). Condensing furnace replacements saved 31–41 GJ/year in the three US studies and appear to be marginally cost-effective, even if a worst-case analysis is used that attributes the entire cost of the retrofit to energy efficiency. Data on packages of weatherization measures are drawn from 21 Pacific Northwest electric utility programs. The principal retrofit measures were various types of insulation and water heating retrofits. Median electricity savings were 4020 kWh per year (16% NAC savings) with a median CCE of 5.4¢/kWh.

Introduction

In 1987, the 65.5 million single-family homes in the United States used 670 billion kWh of electricity and nearly 5 exajoules (1 exajoule = 10^{18} joules) of fuel, representing about one-sixth of total end-use energy [1]. The total energy bill to US single-family households, excluding auto fuel purchases, was over $78 billion in 1987. This expenditure of $1200 per house accounted for 20% of the national energy costs. In order to reduce energy expenditures, large sums are spent on residential retrofits by individual homeowners, government agencies, and utilities. For example, as of late 1987, over 21 million households indicated that they had added at least one energy-saving measure in the previous two years [2]. The US federal and state governments spent approximately $2.4 billion to weatherize low-income residences between 1977 through 1989, under a variety of programs [3]. A recent survey by the Electric Power Research Institute [4] estimates that nearly 15 million residential customers are currently participating in some kind of utility demand-side management (DSM) program. Moreover, from 1981 to 1989, the Bonneville Power Administration spent $427 million on weatherization programs, while programs conducted by California utilities im-

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proved the efficiency of fifteen percent of the state's housing stock between 1984 and 1986 [5, 6]. 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 provides an empirical benchmark for these estimates, improves their credibility, and helps to 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 individual energy-saving measures in existing single-family homes, based on information in the Buildings Energy Use Compilation and Analysis (BECA) database at Lawrence Berkeley Laboratory*. The initial BECA report on measured data for single-family retrofits was completed in 1983 [7]. In updating the single-family database (BECA-B), we have added 135 data points, representing over 33 000 houses to the original database of 145 retrofit projects [8]. Each data point represents aggregate results from a study that reports on metered savings and costs of individual retrofit options or evaluates a package of measures installed as part of low-income or utility weatherization programs. The breadth and quality of data available on individual retrofit options has improved dramatically. For example, we analyze measured data on savings from 14 individual retrofit measures, including attic, wall, ceiling, and foundation insulation, window replacements, heating system retrofits and replacements, central cooling system replacements, water heating retrofits, and warm room zoning. We also report on electricity savings from packages of building shell measures installed in electrically heated homes that participated in utility weatherization programs. In contrast, in our initial study, the only measured data from occupied houses on individual retrofits were for ceiling insulation and flame retention burners, while the number of utility program evaluations has more than doubled. These new studies help fill in longstanding gaps in our understanding of retrofit performance.

*The BECA data base now contains over 3000 records; most of these are for US 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 LBL (510-486-7288).

Data sources

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 contact with program managers and researchers. Potential data are screened and those projects (or certain houses in a study) that do not meet minimum data quality standards are eliminated. For example, 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. 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.

Retrofit 'data points' represent aggregate results from a group of houses. Most data on individual retrofit measures are from research studies and sample sizes tend to be small, typically 5 to 30 houses. However, data points of early utility-sponsored ceiling insulation programs have sample sizes of up to 33 000 homes. 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. Sample sizes are typically between 100–400 homes in studies that report savings from packages of retrofit measures installed in utility-sponsored programs, although one study had over 6000 homes.

Methodology

We collect information on retrofit measures, installed costs, metered pre- and post-retrofit energy consumption, and the physical and demographic characteristics of participating households (e.g., average house size, insulation and glazing levels, type and efficiency of heating system, and average number of occupants) and then calculate energy savings and economic indicators.

Energy savings

In order to account for yearly variations in the severity of weather when determining energy savings, the space heating component of energy use is separated from the baseload and is then normalized to weather for a "standard" year. Space heating energy use can be determined by submetering, or subtracting the non-weather sensitive component (summer baseload). Weather normalization techniques include: submetering of the space heating end use and subsequent normalization, use of the Princeton Scorekeeping Method (PRISM) which involves regression analysis of utility billing data and actual heating degree-days to a variable reference temperature, or scaling of annual space heating use by the ratio of actual to long-term annual heating degree-days (HDDs) to a fixed HDD base. (For this study, energy use was normalized using base 18.3 °C = 65 °F heating degree-days.) Of the 32 data points on individual retrofit measures in the BECA-B database, 22% were submetered, 44% used utility bills weather normalized by PRISM [9], 19% used a regression of utility billing data versus heating degree-days at a fixed reference temperature, and 16% scaled annual space heating by heating degree-days. PRISM was typically used to analyze savings from retrofit packages in the evaluations of electric utility weatherization programs.

The normalized annual consumption (NAC) is calculated by adding the weather normalized space heating and the baseload. The NAC represents total consumption of the main space heating fuel that would occur in a year with typical weather conditions. For gas-heated buildings, the end uses included in the NAC are typically space heat, water heating, and cooking. Electric buildings are usually "all-electric" and thus the NAC represents total household energy use.

Most studies screened for auxiliary space heating fuels, either explicitly or statistically, and eliminated homes in which non-metered fuels, such as wood-heat, were used to meet a significant fraction of the space heat load. Many studies queried the occupants about their use of auxiliary fuels, while some projects established data reliability and quality guidelines in the PRISM analysis (e.g., R^2 had to exceed 0.8)*. Few studies corrected for differences in internal gains or indoor temperature settings between pre- and post-retrofit periods.

Gross versus net savings

Gross savings reflect the difference in weather-normalized consumption between the pre- and post-retrofit period, while net savings adjust for consumption changes that occur in a group of control houses. A control group is used to correct for factors other than the retrofits which could affect changes in energy use over time (response to rising energy prices, increased saturation of home electronics). Unfortunately, about half of the studies did not use control groups, thus calculating net energy savings relative to a control group could not be uniformly implemented. Additionally, most studies that we used screened for some key factors that could account for changes in consumption (e.g., auxiliary heating fuels and occupancy changes). Thus, we rely primarily on gross savings, unless otherwise indicated.

Retrofit costs, economic indicators, and measure lifetimes

Retrofit costs reported in this study reflect direct costs to the homeowner of contractor-

*More recent studies often eleminate houses that have a low correlation coefficient (R^2) or where the NAC is not well defined (high standard errors). The rationale is that the PRISM model offers a meaningful description of the consumption pattern for the fuel under study for the remaining houses.

installed measures. We adjusted nominal retrofit costs to 1989 dollars using the GNP Implicit Price Deflators. 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. Costs may be high because installation techniques have not had a chance to improve over time or because new technologies, by definition, have small market shares, and thus it is difficult to capitalize on economies of scale.

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:

$$\mathrm{SPT} = \frac{\mathrm{FC}}{(\Delta E \times P) - \Delta \mathrm{OMC}} \tag{1}$$

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

The 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 (e.g., the average retail price of natural gas in the US is approximately $6/GJ). The CCE can be expressed as:

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

where
CRF = capital recovery factor $= \dfrac{d}{1-(1+d)^{-n}}$
RC = retrofit cost (in current dollars)
d = discount rate
n = lifetime of measures
Conservation investments are amortized over the measure's expected physical lifetime, using a real (i.e., constant dollar) discount rate of seven percent [8].

Individual retrofit measures: energy savings and economic analysis

Energy savings, retrofit costs, and cost-effectiveness for all individual retrofits are summarized in Table 1 and described in detail in the following Sections.

Ceiling insulation

Data on ceiling insulation retrofits are drawn 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 [10–12]. 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 $1.90/GJ to $4.20/GJ, even in relatively mild climates and cases where some attic insulation was already present (see Fig. 1). Despite their limitations, these initial evaluations do provide compelling evidence documenting the energy-saving benefits of attic insulation.

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 [13]. An evaluation of the Cut Home Energy Costs (CHEC) loan program in Manitoba reported annual average space heating savings of 22 GJ 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 $2.80/GJ [14]. 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% [15]. This study demonstrates that substantial savings can result from ceiling insulation even when the initial consumption is relatively low (117 GJ/year in 6000 $\mathrm{HDD}_{18.3\,^{\circ}\mathrm{C}}$). We did not analyze the economics of this retrofit because much of the labor was provided at no cost by volunteers.

TABLE 1. Average savings and economics of individual retrofits

Measure	Data Source	Prog. Type	Yr	Number of Homes	State(HDD)	NAC pre (GJ)	Average NAC Savings (GJ)	(%)	Retrofit Cost (1989$)	SPT (yrs)	CCE (1989$/GJ)
Shell Measures											
Ceiling insulation (to R-30)	Consol. Gas	U	73	71	MI (6300)	248	33	13	630	4	1.90
" (R-11 to R-30)	Public Serv. Co.	U	77	33,000	CO (6000)	166	21	13	500	6	2.30
" (R-14 to R-31)	Univ. of Illinois	R	78	5	IL (5800)	179	31	17	970	5	3.00
" (R-0 to R-19)	PG&E	U	79	33	CA (2200)	123	16	13	690	6	4.20
" (R-0 to R-19)	PG&E	U	79	16	CA (2700)	100	21	21	680	4	3.10
" (R-11 to R-40)	Manitoba E&M	L	84	47	CAN(10600)	-	22	-	660	8	2.80
" (R-values unknown)	Battelle	U	87	162	OH(6000)	117	14	12	-	-	-
Wall insulation	CEUE	L	82	8	MN (8000)	177*	21	12	1600	11	6.50
"	Int'l Energy	W	84	7	WI (7500)	121*	20	17	810	6	3.40
"	Manitoba E&M	L	84	12	CAN(10600)	-	46	-	850	5	1.60
Foundation insul. in *unconditioned* spaces											
Interior foundation insul. (R-0 to R-11)	CEUE	L	84	8	MN (8000)	136*	21	15	1040	8	4.70
" (R-0 to R-14)	Robinson Tech.	R	88	9	MN (8000)	118*	7	6	1200	33	17.00
Exterior foundation insul. (R-0 to R-10)	CEUE	L	84	5	MN (8000)	116*	12	10	1340	19	11.00
" (R-0 to R-10)	Robinson Tech.	R	88	6	MN (8000)	91*	3	3	1710	127	64.00
Foundation insul. in *conditioned* spaces											
Interior foundation insul. (R-0 to R-11)	Manitoba E&M	L	84	24	CAN(10600)	-	34	-	1020	8	2.90
Replacement windows (R-values unknown)											
	Manitoba E&M	L	84	89	CAN(10600)	-	5	-	940	49	16.00
	Ball State Univ.	L	89	41	IN (5500)	118*	2	1	3350	450	180.00
Warm Room Zoning	LBL	R	85	5	MO (5300)	179	51	28	1580	11	4.40
"	NCAT	R	86	25	PA(5600)	145	33	23	2400	12	8.00
Heating System Retrofits											
Flame retention burners	BNL	R	80	19	NY (5500)	-	19	14	460	2	2.20
"	Mich PSC	R	84	76	MI (7000)	-	34	25	570	2	1.80
"	PECI	R	85	92	OR (4700)	-	23	23	560	5	2.70
Power gas burners	ASE/ORNL	R	85	16	KY (4500)	170*	10	6	560	11	6.10
"	ASE/ORNL	R	85	14	MN (8000)	216*	12	6	560	10	5.10
Electronic vent damper and elec. ignition	ASE/ORNL	R	85	42	MN (8000)	190*	7	4	440	14	9.50
Condensing heat extractors	ASE/ORNL	R	85	43	KY (4500)	141*	20	14	720	7	5.20
"	ASE/ORNL	R	85	35	MN (8000)	179*	7	4	720	23	15.00
Heating and Cooling System Replacements											
Condensing furnace replacement	CEUE	L	82	3	MN (8000)	185*	35	19	4750	20(4)	12.00 (2.50)
"	ORNL	R	85	3	WI (7500)	-	31	-	1880	9(5)	5.60 (3.00)
"	Manitoba E&M	R	85	49	CAN (10,700)	-	41	-	2170	16(7)	4.60 (2.10)
"	Ball State Univ.	L	89	30	IN (5500)	157*	31	19	2110	15(7)	5.90 (2.80)
Central air conditioner replacement	Fleming Group	R	88	12	TX (2900 CDD)	-	2130 kWh	12	2760	13	[14¢/kWh]
Hot Water System Measures											
Water heater wrap	ORNL	U	85	20	OR(5600)	-	970 kWh	-	22	0.5	[0.4¢/kWh]

Key for Table 1

Column	*Explanation*
2	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
3	Program Type
4	Yr = Year of retrofit L = State or city loan program R = Research or demonstration program U = Utility weatherization W = Low income weatherization
6	HDD = Heating degree-days (base 18.3 °C=65°F)
7	NAC_{pre} = Weather-normalized annual consumption prior to retrofit. Projects that use PRISM in energy analysis are indicated by *
8-9	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.
10	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.
11	SPT = Simple payback time (calculated using local energy prices).
12	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.

Wall insulation

Data on wall insulation retrofits are drawn from a research study by the Center for Energy and the Urban Environment [16], from a group of houses retrofitted under Wisconsin's Low-Income Weatherization Program [17], and from the Manitoba CHEC Program [14]. Compared to attic insulation, wall insulation retrofits involve more complex installation procedures, and higher costs. Accurate predictions of savings are more difficult because wall insulation both reduces the conductivity of the wall and reduces infiltration and convective loops within the wall. Also, 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. In addition to difficulties modeling

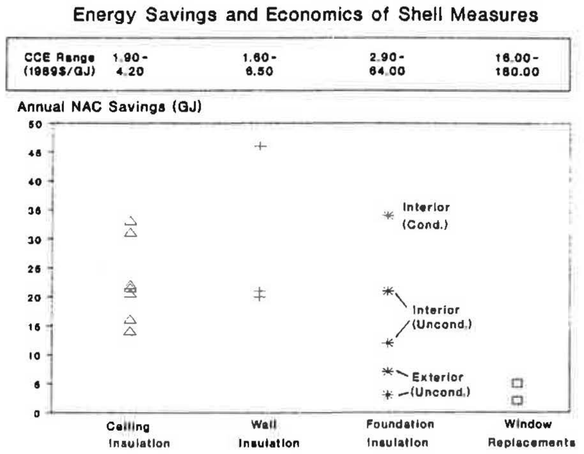

Fig. 1. Annual NAC savings and cost of conserved energy (CCE) for individual shell measure retrofits. Average savings from each study are plotted as one data point along with the range in average CCE values for these studies. For foundation insulation retrofits, "Cond." and "Uncond." refer to conditioned and unconditioned basements.

heat transfer, the actual R-value of existing insulation is rarely known.

The two US studies that examined wall insulation retrofits were conducted in similar climates (7500–8000 $HDD_{18.3\,°C}$) in homes with similar conditioned areas (about 115 m^2). Average NAC savings (20–21 GJ/year) were similar for the two groups (see Fig. 1). However, average retrofit costs (material and labor) in the low-income weatherization program were half that of the research study ($810 vs. $1600). Thus, the CCE was much more attractive for homes that participated in the weatherization program compared to the research study ($3.40/GJ vs. $6.50/GJ). Data from a recent study by the Wisconsin Energy Conservation Corporation (WECC 1989) indicate that wall insulation costs about $800 in a 110 m^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 46 GJ/year after the retrofit. The average CCE was quite low ($1.60/GJ), although the climate is more severe than in the US (10 600 $HDD_{18.3\,°C}$). 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.

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 Center for Energy and the Urban Environment (CEUE) study. Savings were 10% and 15% of the NAC, respectively, for interior and exterior insulation [18] compared to the homes monitored by Robinson Technical Services, where savings were 3% and 6% of the NAC [19]. CCEs were $5/GJ and $11/GJ 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. In both studies, the cost of sheetrock was excluded when calculating the installed cost of interior foundation insulation because we are primarily interested in the incremental costs that are attributable to the insulation component of the retrofit. In most cases, fire codes mandate sheetrock and thus the total cost to the homeowner would be approximately double that shown in Table 1. However, the creation of extra basement living space is a significant non-energy benefit.

The economics of foundation insulation should be significantly improved in houses with conditioned basements because the warmer spaces have more of a driving force to lose heat. The 24 houses in the Manitoba CHEC program that only installed interior foundation insulation in *conditioned basements* reduced consumption by 34 GJ/year [15]. 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 $2.90/GJ.

Window replacements

Window replacements tend to be expensive retrofits, while measured data suggest that energy savings are relatively small (see Fig. 1). An evaluation of window replacements in 41 homes that participated in Indiana's Energy Conservation Financial Assistance Program (ECFAP) found annual savings of 2 GJ [20] at an average cost of $3350 per house. A group of 41 homes that participated in the Manitoba CHEC program had savings of 5 GJ/year in a climate with over 10 000 HDD [14]. Window replacements were the least cost-effective retrofit of all shell options financed by this program. Kinney *et al.* report similar results in their evaluation of New York's low-income weatherization program [21]. Their statistical analysis showed that spending a significant portion of program dollars on window replacements were likely to result in low savings. None of these studies reported the pre-retrofit R-value of the windows.

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 NAC 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 war-room studies in the BECA data base used different methods to create warm zones. In the Missouri study, selected areas of the house were insulated and received infiltration measures [22]. 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). This retrofit strategy reduced consumption in the five-house sample by 51 GJ/year (28% of the NAC) with a CCE of $4.40/GJ. In the Pennsylvania study, attics were insulated and a small, high-efficiency gas heater was installed near the center of the house [23]. 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. Energy consumption was reduced by 33 GJ/year (23% of the NAC). The CCE of $8/GJ was higher than in the Missouri study, in part due to the significant cost of purchasing an additional heating unit. These studies suggest that a warm-room retrofit may be an attractive alternative to conventional weatherization for some elderly residents living in large houses.

Heating system retrofits

Measured data are now available on a number of retrofit options designed to improve the efficiency of heating systems. 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 19–34 GJ/year (14–25% savings) in the three groups at a cost of about $550* [24–26]. The economics of flame-retention burners for oil furnaces are quite attractive, with CCEs of $1.80–2.70/GJ. 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 [27]. 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).

A variety of gas-heating equipment and control options have been tested in R&D projects.

*Percent savings cannot be compared directly 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.

Results of these studies suggest that most of the options designed to improve the efficiency of gas-fired equipment have longer payback times than flame-retention burners for oil-fired systems (see Fig. 2). 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 10–12 GJ/year (6% of the NAC) in each group [28]. Retrofit costs averaged \$560. Compared to current gas prices, these retrofits are marginally cost-effective, with CCEs of \$6.10/GJ and \$5.10/GJ in Kentucky and Minnesota, respectively (Fig. Fig. 2).

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 [28]. The electronic ignition and vent damper combinations cost \$440, giving a CCE of \$9.50/GJ. This retrofit might produce greater savings

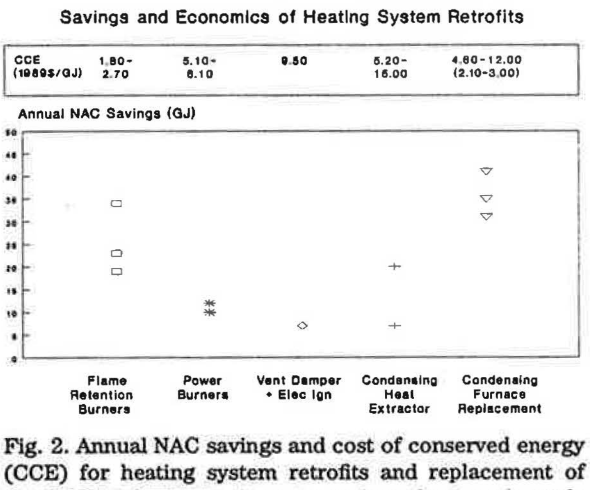

Fig. 2. Annual NAC savings and cost of conserved energy (CCE) for heating system retrofits and replacement of condensing furnaces. Average savings from each study are plotted as one data point along with the range in average CCE values for these studies. Flame retention burners were installed in homes with oil-heating equipment while all other retrofits were installed in gas-fired furnaces.

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. The energy-saving principle behind a condensing heat extractor is to remove the heat of vaporization from the water vapor going up the flue. The only measured data are from a study where the hardware was poorly designed. 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% in Minnesota [28]. Moreover, the electricity use of oversized fans appeared to offset much of the gas savings.

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 Fig. 2). 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 exiting furnace needed replacement — 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 1, two CCE 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 total installed cost of a condensing furnace in Wisconsin is about $1500–1600 [29].

Condensing furnaces were installed in three Wisconsin houses at an average installed cost of $1880. Average energy use decreased by 31 GJ/year, although the variance in savings was quite large (44, 10, and 33 GJ/year respectively). The CCE was $5.60/GJ using the first method and $3.00/GJ using the second method. In an earlier study, the Minneapolis Energy Office reported somewhat larger savings in three homes (35 GJ/year). Average costs were significantly higher ($4750 per house) leading to a CCE of $12.00/GJ or $2.50/GJ 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 two other studies. Hill [20] reported that gas consumption decreased by 31 GJ/year (19% of the NAC) in 30 homes that received condensing furnace replacements as part of Indiana's Energy Conservation Financial Assistance Program (EC-FAP). Installed costs averaged $2110, which produced a CCE of $5.90/GJ ($2.80/GJ using the incremental values). Savings were significantly higher (41 GJ/year) among a group of 49 houses located in Winnipeg Manitoba with 10 600 $HHD_{18.3\,°C}$, almost one third more heating degree-days than Minnesota [30]. The cost of conserved energy was $4.60/GJ or $2.10/GJ 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/GJ). Using the incremental savings and costs, the CCE is in the range $2–3/GJ, which suggests that condensing furnace replacements are highly cost-effective in severe heating climates. The incremental savings and cost approach is representative of a normal turnover of the stock, i.e., replacement as units wear out.

High-efficiency air conditioning replacement equipment

Measured data on retrofit options designed to reduce cooling energy use are still rare. High-efficiency central 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 [31]. Prior to the retrofit, the average air-conditioning energy efficiency ratio (EER) was 6.8 in this group of homes, and increased to 11.4 after installation of high-efficiency equipment. The average cost was $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.

Water heating measures

The energy savings and economics of various options designed to reduce water heating usage come principally from small research studies [32]. A recent study of a sub-sample 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 [33]. 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 1001 kWh/year (17% of water heating electricity use), resulting in a CCE of 0.4¢/kWh. Savings cannot be attributed unambiguously to these options because water temperatures were also lowered, reducing standby losses in an undetermined number of homes in the two groups.

Weatherization packages: results from electric utility programs

Measured data on weatherization programs conducted by US 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. 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 primarily energy-limited. 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).

Large-scale utility weatherization programs began in the late 1970s in the Pacific Northwest and typically focused on reducing energy used for space heat and (to a lesser extent) hot water. Table 2 provides summary information on evaluation results from utility weatherization programs: date of installations, number of houses, average electricity consumption and savings, space heating intensity, average retrofit cost, simple payback, and cost of conserved energy (CCE).

Except for the Hood River Project, all of the programs were pilot or full-scale conventional weatherization programs. 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, which was limited to attic and floor insulation, average contractor costs among the programs ranged from \$1300 to \$2800 per house for these packages of measures. For utility weatherization programs conducted prior to 1985, CCEs were 1.4–7.0¢/kWh with a median CCE of 4.4¢/kWh for these 16 data points (see Table 2), based on gross savings.

Figure 3 shows average space heating intensities before and after retrofit for homes that participated in these programs. Results are arranged chronologically, which highlights the overall regional trend of slowly declining space heating energy intensity over time, which was occurring independent of utility weatherization programs. However, this finding should be hedged because of other confounding factors (e.g., early utility programs may have targeted high users). The median reduction in space heat intensity was about 21% in these 16 programs. More importantly, space heating intensities after retrofit were fairly comparable (70–90 $kJ/m^2HDD_{18.3\,^{\circ}C}$ in site energy) among each group of houses that participated in conventional utility weatherization programs. this provides an important programmatic benchmark for the energy performance that is typically achieved in utility weatherization programs in this region.

Note that average space heating intensities were about 35% lower among the homes that participated in Bonneville Power Administration's Hood River Project. This demonstration project installed additional insulation and glazing compared to standard weatherization programs, and retrofit costs were significantly higher. The Hood River project proved that conservation was a viable resource that could be reliably acquired, and that very low space heat intensities could be achieved as part of the retrofit of existing building stock (53 kJ/m^2 HDD)*.

In evaluating the effects of their weatherization programs, most utilities 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.

*A high percentage of the homes in Hood River used wood for auxiliary heat. We used the "Goodfit" data set that screened for a minimum R^2 of 0.8 to eliminate houses that may have relied on wood to meet a large portion of their heating load.

TABLE 2. Electric utility weatherization programs in the Pacific Northwest

Year Sponsor Project	No. of Houses	Retrofit Measures	Normalized Annualized Consumption Pre-Retro (kWh)	Average Savings (kWh)	(%)	Space Heating Intensity Before	After $(kJ/m^2\text{-}HDD_{18.3C})$	Retro. Cost (89$)	Simple Payback (Years)	CCE (1989¢/kWh)
78 PGE Program	300	IA,IF,WM,DR,WH,CW	23640	3940	17			2260	13	5.4
79 PP&L Program	973	IA,IF,WM,DR,CW,WH	25420	4460	18	114	78	2430	8	5.1
79 SCL Program	133	IA,IF	30110	4180	14			640	5	1.4
79 WWP Program	1030	IA,IF,DR,WM,WH	30010	4450	15			1910	18	4.1
79 WWP Program	810	IA,IF,DR,WM	30140	4350	14	147	112	1830	17	4.0
80 PGE Program	208	IA,IF,WM,DR,WH,CW	24490	4040	16	110	76	2230	12	5.2
80 PP Program	6289	IA,IW,IF,WM,DR,T,WH	32800	8580	26	147	86	1750	5	1.9
81 BPA Pilot	179	IA,IF,IW,DR,WM,CW	28500	6000	21	110	65	2800	18	4.4
81 SCL HELP	132	IA,WM,IF,WH,IW,ID,CW	25870*	4340	17	118	92	2020	16	4.4
81 SCL LIEP	293	IA,IF,IW,WH,ID,CW	21060	3040	14	112	84	1900	23	5.9
81 Idaho ZIP	101	IA,IF,IW,WM,ID,CW	23080	2180	9	108	90	1330	14	5.7
82 SCL HELP	116	IA,WM,IF,WH,IW,ID,CW	25950*	4020	15	125	88	2450	13	5.8
82 BPA Program	229	IA,IF,WM,T,ID	27600*	4800	17	110	78	1980	13	3.9
83 SCL HELP	111	IA,WM,IF,WH,IW,ID,CW	24400*	3820	16	116	90	2320	13	5.7
83 BPA Program	248	IA,IF,WM	25400*	2900	11	98	78	2150	19	7.0
84 SCL HELP	108	IA,WM,IF,WH,IW,ID,CW	24930*	5050	20	123	90	1840	7	3.4
85 SCL HELP	285	IA,WM,IF,WH,IW,ID,CW	25180*	2000	8	100	92	2400	23	11.3
85 BPA/PP&L HOOD RIVER	362	WM,CW,IA,IF,IW,T	24400*	4000	16	78	53	6090	32	14.4
85 BPA RWP	239	IA,IF,WR,CW,WM,ID,IW	23860*	2100	9	92	72	2090	25	9.4
86 BPA RWP	252	IA,IF,WR,CW,WM,ID,IW	23400*	1460	6	78	65	2360	42	15.3
86 SCL HELP	278	IA,WM,IF,WH,IW,ID,CW	22770*	210	1	94	94	2660	228	121.0
		Median Values (N=21)	25200	4020	16	110	86	2150	16	5.4

RETROFIT MEASURES

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

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 space heating intensity is given in site energy.

Economic indicators are calculated using gross savings (and nominal retrofit costs). For later programs, net savings are more relevant. (See Table 3).

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

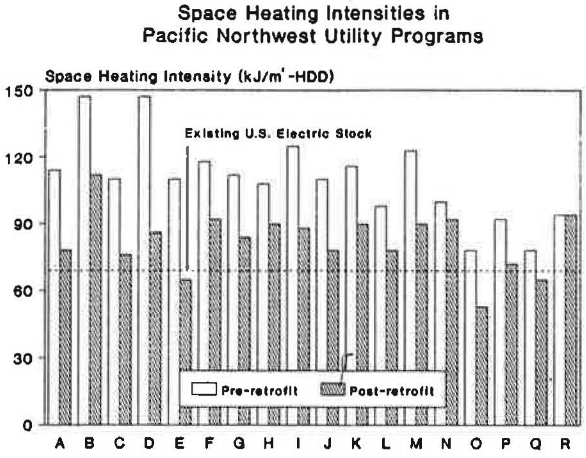

Fig. 3. Average space heating intensity before and after retrofit for homes than participated in electric utility weatherization programs in the Pacific Northwest. For comparison, we show an EIA estimate of space heating intensities for US electric-heated stock based on the 1987 RECS survey. Utility programs are arranged chronological and identified by letters which correspond to the key below.

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

Homeowners presumably altered their energy-consuming behavior and invested in retrofit measures independent of utility programs in response to rising electricity prices. 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 3 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

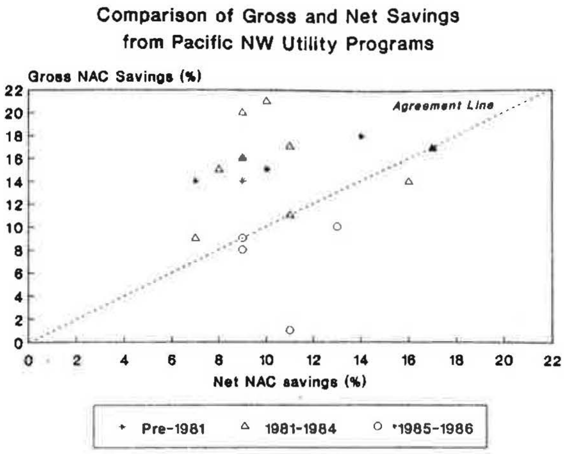

Fig. 4. Comparison of gross vs. net savings for the electric utility weatherization programs from the Pacific Northwest that are shown in Table 3. Net savings include an adjustment for changes in electricity consumption that occurred in control group homes during the same time period.

programs and over time. In Fig. 4, 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.

Conclusions

This study provides a comparative analysis of measured data on the performance and cost-effectiveness of energy-saving measures in existing single-family homes. Both ceiling and wall insulation were quite cost-effective, with normalized annual consumption (NAC) savings ranging between 12–21% in 10 retrofit projects, and average cost of conserved energy (CCE) values between $1.60–6.50/GJ. Retrofit technique (interior vs. exterior insulation) and basement condition (unconditioned vs. conditioned) strongly influenced the level of energy savings in homes that installed foundation insulation,

TABLE 3. Gross vs. net savings: 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 = $(NACpost/NACpre)_{control} * [(NACpre)_{treatment} - (NACpost)_{treatment}]$

although payback times were generally quite long. Window replacements were found to have small NAC savings (2–5%) and were not particularly cost-effective (CCE > \$15/GJ). Flame retention burners for oil furnaces produced significant savings (19–34 GJ/year for the three studies in our data base) and had CCEs of less than \$2.70/GJ. Several retrofit strategies that improve the efficiency of gas furnaces produced annual savings ranging between 7–20 GJ/year (4–14%), with CCEs that were comparable to current gas prices (\$5–7/GJ). Condensing furnace replacements saved 31–41 GJ/year in the three US 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 be highly cost-effective.

Data on packages of weatherization measures are drawn from 21 Pacific Northwest electric utility programs. The principal retrofit measures were various types of insulation and water heating retrofits. Median electricity savings were 4020 kWh per year (16% NAC savings) with a median CCE of 5.4¢/kWh.

This compilation highlights the fact that recent field studies 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 retrofit performance in mild and cooling climates, cooling retrofits, impacts of retrofits on peak electricity demand, reduction of losses from duct work, as well as submetering of inexpensive measures that produce small savings, but may still be cost-effective.

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