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MEASURED ENERGY SAVINGS FOR INDIVIDUAL RETROFIT MEASURES IN SINGLE-FAMILY BUILDINGS

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INTRODUCTION

This study reports on the single-family component of an ongoing activity at Lawrence Berkeley Laboratory: the compilation and comparative analysis of measured data on the performance and cost-effectiveness of energy-saving measures in new and existing buildings. The Buildings Energy Use Compilation and Analysis (BECA) data base now contains well over 2500 records; most of these are for U.S. buildings.[1]

An initial report on measured data for single-family retrofits (BECA-B) was presented at the 1984 ACEEE Summer Study (Goldman 1984); additional results for multi-family retrofits were presented at the 1986 and 1988 Summer Studies (Goldman et al. 1988). In updating the single-family data base, we have added 77 data points, representing over 17,000 houses. In particular, we have emphasized energy savings and cost data on individual retrofit measures. The data base now contains measured savings and costs for both retrofit "packages" and individual measures, including furnace retrofits and furnace replacements; central air conditioning replacement; wall, foundation, and ceiling insulation; house-doctoring; warm-room zoning; and water heating measures.

-The next section provides an overview of recent trends in energy conservation programs for existing residences. This provides background for interpreting measured results from the data base. We then briefly describe the sources of data and our analytical approach, followed by a summary of savings and cost-effectiveness results. A concluding section discusses the implications of these data, both for future retrofit programs and for continued improvements in the measurement and documentation of retrofit performance.

ENERGY CONSERVATION PROGRAMS FOR EXISTING BUILDINGS

To establish a context for the specific results presented below, we first review the changing status of three types of programs representing the principal sources of measured data on single-family retrofits: utility conservation (customer services) programs, the federal-state Low-Income Weatherization program, and research and development studies which include monitored field tests.

Electric and Gas Utility Programs

In the mid-1980's, the focus of many utility demand-side programs began to shift from the residential sector to commercial and industrial customers, and within residences from single-family to multifamily buildings. Several first-generation retrofit programs were 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). These programs contributed to the widespread view that many of the shortest-payback measures were reaching saturation in existing single-family

[1] Components of the BECA data base 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); residential water heating systems (BECA-D); and validations of computer load models (BECA-V). Reports on each compilation are available through the Energy Analysis Program at LBL (415-486-7288).

organizations, are typically well-controlled experiments using small samples of test and control houses to measure the performance of individual retrofit measures such as foundation insulation, power gas burners, condensing heat extractors, and high-efficiency replacement equipment. There is a growing tendency for these field research projects 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 (equipment status, HVAC flows and temperatures, etc.). 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.

The next section discusses how data from each of these sources are reviewed, adjusted to comparable conditions, and then analyzed.

DATA SOURCES AND ANALYSIS METHODS

The BECA data compilation relies on monitored performance data collected by others. However, we often extend the original analysis, conducting additional screening and analysis and (where necessary) adjusting the reported data to normalized weather and operating conditions. Information on the measured performance of retrofits in single-family buildings is obtained from a variety of sources: literature reviews, conference proceedings and journals, and contacts with program managers and researchers. Some projects with measured savings are not included in the analysis due to problems with data quality, completeness, or comparability. The available data are screened to help assure that savings are related to the actual retrofit, not unaccounted-for external factors. Typical screening criteria include: no supplemental heat (e.g., wood), no changes in occupancy during the study period, and continuous billing histories.

In most cases, a retrofit "data point" represents aggregate results from a group of houses. Sample sizes vary, with R&D projects generally tending to smaller sample sizes (10-30 houses), while studies evaluating utility and Low-Income Weatherization programs can represent aggregate results from thousands of households. As noted, data from 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. In cases where a number of retrofit measures are installed in the same house, it is not possible to reliably estimate savings for individual retrofits using the measured data alone.[2] In this report, all the data on individual retrofit measures are from houses where only one measure was installed.

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 1986). For fuel-heat buildings, the end uses included in the normalized annual energy consumption (NAC) were space heat, hot water, and, in some cases, cooking. Most of the electric-heat buildings were "all-electric" so the NAC includes all household end uses. Where only seasonal or annual energy data were available (rather than monthly billing periods, allowing a weather-correlation using PRISM), estimated space heat energy use was weather-normalized using the ratio of that year's (base 65° F) heating degree days (HDD) to HDD for an average year.

[2] Where multiple measures are installed, disaggregating savings by measure requires some combination of: detailed on-site monitoring, supplementing measured data with building simulation modeling (see Diamond et al. and Kaplan et al.), or possibly the application of multivariate statistical analysis to a suitably large and high-quality data set.

achieved in large-scale programs--or where replacement exterior siding is needed, anyway, and does not represent an added cost of wall insulation.

The effects of foundation insulation 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: 10 and 15%, respectively, for interior and exterior insulation (Quaid et al. 1988) compared to the homes monitored by Robinson Technical Services, at 3 and 6% (Robinson et al. 1989). Payback times were 17 and 21 years for the houses in the MEO study, but much longer for the houses monitored by Robinson. The apparent discrepancy in performance may be due to the fact that the Robinson study focused on conductive losses only and therefore took steps to reduce basement area infiltration prior to measuring energy use for the pre-retrofit season. 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, interior foundation insulation produced greater savings than exterior insulation, although at a somewhat higher retrofit cost. It is important to note that interior sheetrock and finishing costs were included in the interior foundation retrofit. In some cases, the extra basement living space is a significant non-energy benefit that may make the interior foundation insulation retrofit attractive despite a long payback period.

Warm-Room Experiments

Creating "warm rooms", that is zoning and weatherizing only a portion of a house, can produce large savings (about 25%) at costs similar to those of conventional weatherization programs which achieve 10-15% savings. The warm-room concept was designed especially for elderly, low-income homeowners who 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 data base 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, 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.

Heating System Measures

Measured data are now available on a number of retrofit options designed to improve the efficiency of heating systems, or to install high-efficiency replacement equipment. Energy savings from retrofitting oil furnaces with flame-retention burners have been documented in studies in several states (New York, Michigan and Oregon). This option reduced average oil consumption by 20-32 MBtu (14-25% savings) in the three groups at a cost of about $550 (Hoppe et al.

Average gas usage was reduced by 20% following furnace replacements in 33 low-income Wisconsin households. It is difficult to assess the results in detail because the project did not collect data on the efficiency or capacity of the replacement furnaces. The economics were somewhat favorable, with a CCE of $6.10/MBtu (Horowitz et al. 1987).

Condensing furnaces were installed in three Wisconsin houses at an average installed cost of $1880. The energy savings averaged 27 MBtu but had a wide scatter: 42, 9, and 31 MBtu. The average payback time was 9 years and the CCE was $5.90/MBtu. An earlier study conducted by Minneapolis Energy Office reported comparable savings on average (28 MBtu), but significantly higher average costs ($4750 per house). Thus, the economics were much poorer, with a payback time of 24 years and CCE of $15.00/MBtu. In this case, the cost of a condensing furnace was unusually high because the product was new on the market at that time. The current installed cost of a condensing furnace in Wisconsin is $1500-$1600.[3]

If we had used the second approach to calculate cost-effectiveness, the resultant energy savings would be lower than those shown in Table 1 because only the difference in energy use between a new baseline model (presumably more efficient than the old furnace) and the high-efficiency model would be attributed to higher efficiency. At the same time, we would consider only incremental costs, rather than the full cost of the replacement equipment; we estimate that incremental costs would range from $300 to $600. Thus, compared with the first calculation, costs are reduced by a factor of five or more while the energy savings are reduced by only about fifty percent. We cite the more conservative estimate of cost-effectiveness in Table 1 (i.e., total, not incremental, costs and savings) to provide an upper bound on the economics of furnace/boiler replacement (see Cohen et al. 1990 for a more detailed discussion).

High-efficiency Air Conditioning Replacement Equipment

Replacement of air conditioners with high-efficiency equipment was examined in 12 houses in Austin, Texas (Hough et al. 1989). Prior to the retrofit, the average Energy Efficiency Ratio (EER) was 6.8, which increased to 11.4 after installation of high-efficiency equipment, at a cost of about $2760 per house. Electricity usage 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.

Hot Water System Measures

Data from the Hood River Project indicate that water heating retrofits are highly cost-effective, although the savings for individual measures contain some inconsistencies (Brown et al. 1987). In a sample of 20 homes with submetered water heating energy, water heater tank wraps were found to save 972 kWh per year (22% of water heating electricity use) 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 per year (17% of water heating electricity use), resulting in a 0.7 year payback. In an unknown percentage of the homes in each group, the water temperature was also lowered, reducing standby losses.

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Retrofit Packages

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[3] Schlegel, Jeff (Wisconsin Energy Conservation Corporation), personal communication, June, 1990.

DISCUSSION

In this concluding section, we discuss some of the broader issues suggested by the data, when considered in light of earlier BECA retrofit data, and in the context of current and potential future retrofit programs.

A Decline in Savings and Cost-effectiveness?

A key question raised by the recent data on individual residential retrofits is why the economics of many measures appear marginal, as indicated by the long payback periods and relatively high CCEs shown in Table 1. Our previous work, in the 1984 BECA compilation of single-family retrofit data, showed energy savings of 20-25% from "packages" of measures (primarily envelope insulation). Paybacks were attractive (5-9 years), with CCEs significantly less than current gas and electricity prices (Goldman 1984). The more recent data, concentrating on individual retrofit measures, show wall and foundation insulation saving about 10-15% of the space heat fuel, the less expensive HVAC system measures saving roughly 5%, and more costly system changes producing about 15-20% savings in the space heat fuel. For some of these retrofit measures, costs are also substantially higher than those seen in earlier studies; this contributes to longer payback times and higher costs per unit of energy saved. To what extent do these newer data indicate a decline in expected savings and cost-effectiveness, as we move into "second-generation" retrofits--and what does this suggest for program design?

There are a number of factors at work, some reflecting changing characteristics of the existing residential stock (and thus different retrofit opportunities), while others simply reflect the nature of the studies that produced our measured data:

- Single measures vs. retrofit "packages" - As noted, the theme of our updated analysis was to look at projects where an individual retrofit measure had been installed and monitored. In many cases, an effective implementation program would look for practical combinations of measures to install in each house, in order to maximize cost-effective savings and spread program operating costs over a larger base.

- Lower energy consumption base - Unlike many of the data points in our previous BECA compilation, reflecting utility programs and DOE Weatherization programs, homes in the recent studies (Table 1) set were often selected for retrofit not because they offered the best energy-saving opportunities, but because they provided the good opportunities to measure the impact of specific retrofits. In many cases, the houses in these studies were already fairly energy-efficient prior to retrofit, thus reducing the potential for savings (in absolute, if not necessarily in percentage terms). For example, the Minnesota houses where foundation insulation was tested had already received "first-generation" envelope retrofits (attic and wall insulation).

  Comparing the research studies from the 1984 and 1989 BECA-B analyses, homes with gas heating had similar energy consumption, but homes in the newer studies were typically smaller and located in colder climates. Adjusting for climate and floor area, the energy intensity of the gas-heated homes in the latest update is approximately two thirds of that of the comparable group from the 1984. This may explain some of the less favorable economics of more recent studies.

- Economics of research studies - A number of the studies shown in Table 1 were undertaken to answer specific questions (e.g., actual savings from foundation insulation, a measure difficult to simulate with computer models), rather than to demonstrate cost-effective

This leads us to conclude that new measurement approaches may be needed, as an alternative to either whole-house (utility bill) data or continuous end-use metering, to produce reliable but affordable data on the real performance of individual measures. Examples include innovative use of short-term monitoring, controlled in-situ tests, and other forms of diagnostics that can be reliably extrapolated (using simulation models) to estimate long-term performance under a range of real (or realistic) conditions. One difficulty with this idea, at present, is that the available diagnostic tests (e.g., pressurization using blower-doors, "co-heating," flue-gas efficiency measurements) all produce specialized performance indicators. Additional, often complex analytical steps would be needed needed to convert these diverse indicators into a single figure of merit such as annualized energy savings.

Capturing Future Conservation Potential in Single-Family Homes

A logical question follows from analyzing the results for individual retrofit cases: To what extent can this experience be replicated elsewhere? What is a realistic estimate of the remaining conservation potential in the U.S. single-family stock? A thorough answer requires data on the building stock that are not yet publically available, and is also beyond the scope of this analysis.

An earlier effort to extrapolate BECA results for multifamily retrofits to stockwide energy-saving potential produced a range of estimated savings 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 multifaily database, was relatively low. For retrofits in single-family homes, the situation is more complex. A number of the measures included in BECA results are already present in the existing stock, but to varying degrees and not always well-quantified.

The best single data source on national stock characteristics is the Residential Energy Consumption Survey (RECS) conducted periodically by the U.S. DOE Energy Information Administration (EIA 1989). Although RECS is an important resource for many purposes, there are some significant gaps and limitations in the data collected. Most notably, heating equipment and distribution system characteristics are not well specified. 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. Collaboration between EIA and the many utilities already involved in on-site energy audits offers one promising avenue.

Table 3 summarizes the data that are in RECS on energy-saving features of the single-family U.S. stock (DOE/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 percentage of recently-constructed, post-1980 homes (many located in the mild climates of the South and West) that will lack the basic energy-saving features listed in Table 3.

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Table 1. Average Savings and Economics of Individual Retrofits

Measure	Data Source	Prog. Type	# of Buildings	State (HDD)	Savings MBtu	%[a]	Cost[b] (1989$)	SPT (yrs)	CCE (1989$/MBtu)
Shell Measures									
Ceiling insulation (R-0 to R-19)	PG&E	U	33	CA (2200)	15	13	690	6	4.40
" (R-0 to R-19)	PG&E	U	16	CA (2700)	20	21	680	4	3.30
" (R-11 to R-30)	Publ. Serv. Co.	U	33,000	CO (6000)	20	13	500	6	2.40
" (to R-30)	Consol. Gas	U	71	MI (6300)	33	13	630	4	1.80
" (R-14 to R-31)	Univ. of Ill.	R	5	IL (5800)	28	17	970	5	3.20
Wall insulation	MEO	R	8	MN (8000)	19	12	1600	12	7.30
"	1984 WI LIW	L	7	WI (7500)	19	17	810	6	3.60
Interior foundation insul. (R-0 to R-11)	MEO	R	8	MN (8000)	20	15	2090	17	10.00
" (R-0 to R-14)	Robinson Tech.	R	9	MN (8000)	6	6	2180	61	32.00
Exterior foundation insul. (R-0 to R-10)	MEO	R	5	MN (8000)	11	10	1340	19	12.00
" (R-0 to R-10)	Robinson Tech.	R	6	MN (8000)	2	3	1710	127	67.00
Warm room zoning	LBL	R	5	MO (5300)	48	28	1580	11	4.70
"	NCAT	R	25	PA(5600)	31	23	2400	12	8.50
Heating and Cooling System Measures									
Flame retention burners	State of OR	R	92	OR (4700)	20	23	560	5	2.80
"	Brookhaven	R	19	NY (5500)	22	14	460	2	2.90
"	State of MI	R	76	MI (7000)	32	25	570	2	1.90
Power gas burners	ASE/ORNL	R	16	KY (4500)	10	6	560	11	6.40
"	ASE/ORNL	R	14	MN (8000)	11	6	560	10	5.40
Elec. vent damp. and elec. ign.	ASE/ORNL	R	42	MN (8000)	6	4	440	14	10.00
Condensing heat extractors	ASE/ORNL	R	43	KY (4500)	19	14	720	7	5.40
"	ASE/ORNL	R	35	MN (8000)	7	4	720	23	16.00
Cond. Furn. Repl. Unit	MEO	R	3	MN (8000)	28	16	4750	24	15.00
"	ORNL	R	3	WI (7500)	27	-	1880	9	5.90
Forced Draft Furn. Repl. Unit	MEO	R	13	MN (8000)	19	13	3040	22	14.00
Forced Draft Boil. Repl. Unit	MEO	R	4	MN (8000)	30	13	3590	17	10.00
Furn. Repl. (Eff. Unknown)	1984 WI LIW	L	33	WI (7500)	26	20	1860	10	6.10
Central air conditioner replacement	Fleming Assoc.	R	12	TX (2900 CDD)	2130 kWh	12	2760	13	[14¢/kWh]
Hot Water System Measures									
Water Heater Wrap	Hood River	U	20	OR(5600)	970 kWh	-	22	0.5	[0.4¢/kWh]

Notes:

U = Utility; R = Research; L = Low income; HDD = Heating Degree-Days; SPT = Simple Payback Time; CCE = Cost of Conserved Energy

[a] Percent savings refers to the main space heating fuel only.

[b] For central heating and cooling system replacements, the entire cost is attributed to higher efficiency.