LBL-25126

ESTIMATING CONSERVATION POTENTIAL USING BECA DATA

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February 1988

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Abstract

This report describes our first attempt to extrapolate the measured energy savings found in two BECA compilations to the relevant portions of the U.S. building stock. We estimate a savings potential of 0.2 -0.5 Quads/year (resource) from retrofitting the existing multifamily stock, and roughly 0.2 - 0.3 Quads/year (resource) from upgrading thermal features in new, all-electric homes built in the next decade. While these estimates are based on actual *measured* results rather than a theoretical economic and engineering optimum, they do *assume complete saturation* of the relevant stock segments. Costs of conserved energy are generally well below the current prices paid for that energy. The total cost to implement these measures is estimated to be about $30 billion for intensive retrofits of multifamily buildings and $44 billion to upgrade new, electrically-heated homes.

INTRODUCTION

DOE has supported a series of building energy-use compilations, the "BECA" database at LBL, for seven years. The goal of these compilations is to document the *measured* energy performance of new buildings and equipment, and measured energy savings from retrofits. In many cases, the BECA data also document the cost-effectiveness of innovative design and retrofit measures. The goal of each compilation is to collect, analyze, and compare reliable energy-use and cost data. Because BECA data are compiled from other (primary or secondary) sources, they do not represent a statistically chosen sample. Nevertheless, because the most extensive compilations contain results from thousands of buildings throughout the United States, they can tell us a great deal about the nationwide energy-saving potential based on actual measurements, rather than the engineering estimates and simulations which have been relied on until now. This report describes an initial effort to extrapolate the measured energy savings found in two BECA compilations to the corresponding segments of the U.S. stock: retrofitted multifamily buildings and new, electrically-heated, single-family houses.

Organization

We begin by summarizing the results, then briefly describe the extrapolation methods. The report concludes by listing actions that would improve the accuracy of the extrapolations. Appendixes A and B document the methods, assumptions, and results for the two extrapolations. Many key assumptions do not appear in the Results section (below) so it is essential to refer to the Appendixes.

RESULTS

We prepared national extrapolations based on two BECA compilations: retrofitted multifamily buildings (a subset of BECA-B) and new, all-electric single-family houses (a subset of BECA-A). The BECA-MF extrapolation estimated the potential energy savings from retrofitting the existing stock of apartment buildings. In contrast, the BECA-A extrapolation estimates the potential savings from energy-efficient designs in new, all-electric homes that will be built over the next ten years. Thus, the BECA-A extrapolation requires additional assumptions about future housing starts and fuel choice. In both cases, however, the starting point is *measured* savings and their associated costs for many hundreds of buildings, as documented in the respective BECA databases.

Our goal is to extrapolate the savings to the entire stock. However, there are notable gaps in the coverage of the BECA data, in terms of building types, climate zones, and fuel types (to name a few). For example, we must extrapolate space heating savings in cold regions, which are well-documented in BECA records, to milder climates with little or no measured data. Such an extrapolation may be imprecise, because the measures documented in BECA may not apply to different building types or because heating-related shell or system measures also affect cooling.

Ideally, the energy savings from the BECA results should be adjusted to reflect all the key determinants of energy use for the nationwide stock. The determinants for space heating include size of unit, heating system type and efficiency, thermal characteristics of the shell, climate, occupant habits, inside temperatures, and conservation measures already implemented. Only a few of these adjustments are in fact possible, however, because much of this information is not available for the stock, from either existing national surveys or forecasting models. We generally used published data from national surveys for the extrapolations; however, we also relied on interpretations by Meyers (1986) and others. All savings are expressed in resource energy.

Retrofits of Multifamily Buildings Could Save About 0.2 - 0.5 Quads/Year

The BECA Multifamily (MF) database currently includes over 200 U.S. retrofit projects, representing 20,000 apartment units (Goldman et al., 1988). With few exceptions, multifamily buildings in the BECA database have five or more units. Retrofit efforts focused on reducing space heating (and domestic hot water) energy. Measured energy consumption data come principally from utility bills, and thus typically include all end uses of the space heat fuel.

We classified the BECA MF buildings into "typical" and "intensive" retrofit packages, segmented by key building and heating system types. Major market segments included: 1) centrally-heated, fuel buildings with steam distribution systems, 2) centrally-heated, fuel buildings with hot water distribution systems, 3) fuel-heat buildings with individual apartment unit space heaters, and 4) electric resistance-heated buildings.

Median fuel savings for typical retrofit efforts in fuel-heat buildings with central heating systems ranged between 6 and 18 kBtu/ft (13-15% of pre-retrofit fuel usage). More intensive retrofit efforts in these two groups yielded savings of about 45-50 kBtu/ft. Typical savings were 10 kBtu/ft^2 (or about 10% of pre-retrofit fuel consumption), for fuel-heat buildings with individual unit heating, although our sample is relatively small. Finally, median electricity savings were about 10% for individually-heated, electric baseboard, buildings that installed typical retrofits, while savings were 19% for intensively retrofitted, electrically-heated buildings.

The measured savings from each group of BECA MF buildings were then extrapolated to the entire multifamily stock using information on consumption and building characteristics obtained from the 1984 Residential Energy Consumption Survey (RECS), a statistically representative sample of the U.S. building stock (EIA 1987) (see Appendix A for detailed summary of the approach).[1] The savings estimates for buildings with 5+ units are based on *direct* extrapolation, while estimates for 2-4 unit buildings — for which there are no BECA data — are *indirect*. In other words, the direct extrapolations are based on buildings with similar characteristics, such as, heating system and fuel type, and vintage. Savings for 2-4 unit buildings are based on savings obtained in 5+ unit buildings with similar characteristics. Figure 1 shows the mapping of savings from "typical" and "intensively" retrofit BECA buildings to the stock of U.S. multifamily buildings.

Our analysis accounts for the disproportionately high number of multifamily buildings in the BECA database that are located in colder climates and the fact that these buildings use slightly more energy prior to retrofit than the U.S. multifamily stock (even after adjusting for climate differences). After adjusting for differences in climate and initial pre-retrofit consumption between BECA MF buildings and the U.S. multifamily stock, typical retrofits of U.S. multifamily buildings could save about 0.2 Quads per year (in resource energy), while intensive retrofits could save about 0.5 Quads per year (see Figure 2 and Appendix A for detailed discussion of the adjustments).[2] These results suggest that current energy consumption in the multifamily sector could easily be reduced by 9-22%.[3] The strength of this analysis is that it is based on documented results from existing conservation programs and that it is benchmarked to actual consumption of the existing stock. Our analysis of the uncertainty in the stock savings estimate indicates that the 95% confidence interval for installation of typical retrofit is 0.2 quads ±0.09, while it is 0.5 quads ±0.2 for intensive retrofits (see Appendix A for discussion of the uncertainty analysis).

Payback times were only two years for typical retrofits installed in fuel heated homes and about five years for intensive retrofits, corresponding to a cost of conserved energy (CCE) of less than $2/MBtu. In contrast, the median payback time was over twenty years in our relatively small sample of retrofitted electric-heat buildings. The long paybacks in electrically heated homes were attributable in part to high retrofit costs (over $1500/unit). We estimate that retrofitting the entire multifamily stock with the "typical" retrofits would cost $7.5 - $11 billion; for the intensive retrofits, $27 - $32 billion.

Upgraded Construction Practice Could Save 0.23 - 0.36 Quads/Year in New, Electrically Heated, Single-Family Homes

The BECA-A compilation contains space heating data on about 800 new houses in the United States, Canada, and Europe. Most of the houses are located in colder regions. Unlike the retrofit databases, the BECA-A compilation lacks an obvious baseline, that is, data on space heating energy use of houses built to "current practice." A major subset of the BECA-A database are the homes that participated in the Bonneville Power Administration's Residential Standards Demonstration Program (RSDP) (Meier et al., 1986). BPA sponsored the design and construction of several hundred electrically heated homes. The RSDP data set includes a baseline of comparable (and monitored) baseline energy and building characteristics data for an equal number of electrically-heated homes built to current practice. The measured energy savings -- after adjusting for differences in the two groups -- was about 45%.

[1] Because RECS does not collect data on distribution system type, we assume that centrally-heated fuel buildings built prior to 1950 have steam distribution systems, while those built after 1950 use hot water distribution. We assumed that most buildings constructed since 1980 were not eligible for retrofitting because of more energy-efficient design standards included in recent building codes.

[2] We also performed a sensitivity analysis in which we extrapolated savings in individual-heated fuel and electric buildings with two to four units based on measured data from typical retrofits of single-family houses (about six million units or 27% of the total multifamily sector). After all adjustments, the savings potential was about 0.28 quads, an increase of about 0.06 Quads (see Appendix A for details).

[3] Percent reduction in energy consumption of main heating fuel. Note that the percent reduction in space heating energy is much higher, but can not be separated out with the required accuracy using only utility bills.

A simple extrapolation, based on the 2500 kWh/year savings found in the RSDP and the number of electrically homes that are expected to be built throughout the country in the next decade (as projected by the Residential Energy Model), yielded a potential 0.22 Quads/year savings (see Figure 3) (McMahon 1985). For the purposes of comparison, these savings represents about 45% of the 0.47 Quads/year that REM projects will be used by those new houses. The raw extrapolation implies that the average new electrically heated house will use about 9100 kWh/year for space heating. It is difficult to calculate confidence intervals for this (and subsequent) estimates because the stock estimate is a projection. However, the standard deviations of the original RSDP savings have been superimposed to indicate the *minimum* range.

We made four adjustments in the "raw" extrapolation using available data. The adjustments included heating system type, floor area, climate, and a final calibration to the REM baseline energy use.

In the first step, we adjusted the savings for variations in savings of the heating system types. For example, the energy savings in RSDP houses with central furnaces were much greater than those for heat pumps. We adjusted the initial savings estimate to reflect differences in the mix of heating types in RSDP and REM. This increased the extrapolated savings by almost 50%, to 0.32 Quads.

Next, we adjusted the savings to reflect differences in floor area, because the RSDP houses were smaller than the national average for all new houses (electric and fuel heat). As a result, the extrapolation increased another 15%, to 0.36 Quads. There is, however, considerable uncertainty in this adjustment, because we were not able to distinguish the floor areas of new electrically-heated homes from fuel-heated homes.

Most of the new electrically-heated homes will be built in climates considerably warmer than the Pacific Northwest. So, in this step, we reduced the projected savings by a climate-adjustment factor. Savings dropped by about 40%, to 0.23 Quads.

We also made similar adjustments for the RSDP control houses and found that measured space heat consumption was about 40% lower than REM projections for average new houses. If we adjust the RSDP baseline to coincide with the higher REM value, then the savings climb to 0.32 Quads. This discrepancy should be the focus of more detailed examinations.

In summary, measured savings of over 45% have been demonstrated for new, electrically-heated houses in the Pacific Northwest. Similar upgraded construction practices for new, electrically-heated single-family houses across the U.S., to be built in the next decade, could save at least 0.23 Quads/year, and perhaps as much as 0.32 Quads. Incorporation of measured data for milder climates, if available, could greatly improve the confidence in this estimate.

The savings were accomplished principally through higher levels of insulation, extra layers of glazing, and tighter construction. No attempt was made to estimate the effect of improved efficiency for electric heating systems. These measures cost about $5700 per home, representing a cost of conserved electricity of about 8¢/kWh. Alternative combinations of conservation measures appeared to be able to achieve similar savings, but for a lower cost.

FUTURE WORK TO IMPROVE THE ACCURACY AND VALUE OF BECA EXTRAPOLATIONS

The two examples demonstrate that it is possible to extrapolate BECA savings data to the whole country. The results are interesting in themselves, but they also allow us to show the framework which could be used for much higher quality data. This section describes future work that would improve the accuracy of the extrapolations and generally make the BECA data more useful for national policy analysis. The work falls into two categories: that directly related to the BECA compilations and that done by other agencies or groups.

Improving the Breadth and Quality of Data in the BECA Compilations

Coverage. The two extrapolations could still be greatly improved. As indicated in the discussion of each adjustment step, there are major gaps in coverage of BECA data. This can only be remedied by increasing the quantity and quality of the data in the compilations. For example, the multifamily database has few examples of retrofits to 2-4 unit buildings or results from retrofits performed in mild climates. There is also a need for submetered data for multifamily buildings. Many such studies are in the backlog of unexamined reports and data, but we have not had the staff to enter and analyze them. Thus, a renewed emphasis on traditional BECA data compilation and analysis is essential to improve the extrapolations.

New extrapolations. Extrapolations for other compilations are feasible, although the problem of limited coverage plagues them in varying amounts, too. We believe that it is important to apply the extrapolation methodology to a commercial buildings compilation. The new commercial buildings database (BECA-CN) is probably closest to ready for extrapolation. Thanks to new data released by the Non-Residential Buildings Energy Consumption Survey (NBECS), this extrapolation may include extrapolations of peak power as well as energy savings. We are planning to update the retrofitted commercial buildings compilation, BECA-CR, this year. If the update proceeds smoothly, an extrapolation of savings from commercial retrofits would be possible in FY 89.

We are rapidly expanding our database on measured energy use of refrigerators. The refrigerator compilation is unusual in two ways. First, the database covers the whole spectrum of refrigerator efficiencies, so it comes with its own baseline. Second, we have the laboratory test values for each unit. As a result, we can compare the measured energy use of energy efficient refrigerators to similar inefficient models and to the laboratory test values for both. All three values can be compared to the assumptions currently used in REM and utility demand forecasting models (including peak demand). This would be the first extrapolation of potential savings from higher-efficiency appliances based on measured energy use.

Even though the water heating compilation is presently dormant, we have continued to collect reports and leads with the intent of re-activating it in FY 88-89. We expect that the update will have broad coverage, both geographically and with respect to measures and conditions. In the earlier water heating compilation, we found that most water heating conservation studies come with excellent baseline data. This will simplify the savings extrapolations and comparisons with models and forecasts.

The energy used for cooling is becoming increasingly important. BECA-CN is the only compilation with cooling data. A major theoretical effort is needed prior to beginning a compilation on residential cooling for both new homes and retrofits. We have not yet developed a technique of standardizing the results so as to make different buildings comparable. Our recently-developed synthetic data procedure (Meier et al., 1988) provides a tool to bench-test standardizing procedures without reliance on extensive field data.

Baseline data. We hope to encourage the major surveys to collect more detailed data on the key determinants of energy use. At the same time, we have not fully exploited existing baseline sources. For example, we have access to RECS and NBECS tapes but do not have the staff to create the cross-tabs needed to match BECA data.

New adjustments. Two further adjustments to the BECA-A data are possible but could not be undertaken in the time available. An inside temperature adjustment could be derived from the RECS temperature data. The shell characteristics adjustment needs the National Association of Home Builders (NAHB) database for new construction.

External Activities to Improve the Extrapolations

The savings extrapolations rely heavily on baseline energy and building characteristics data from sources outside of BECA. Thus, a major effort is needed to improve the quality (and sometimes quantity) of external sources. Some of these tasks include:

EIA collaboration. We would like to work with The Energy Information Administration to ensure greater relevance of the collected data to building energy analysis. For example, the energy data currently being collected for master-metered multifamily units are imputed from single-family homes. (It is probably no better than computer simulations.) Thus, the energy use for 30% of the nation's housing stock is based on essentially no direct data. EIA might also consider collecting conservation activity for multifamily buildings — perhaps as part of its landlord survey. The inclusion of peak power data in NBECS is an example of successful coordination.

Presently, EIA does not weather-correct the residential energy data. Weather correction is a complex procedure that, if not carefully undertaken, can increase the error. However, if accurately done, the weather-corrected data would improve the quality of all RECS-based energy analyses. For new homes, EIA might consider oversampling newly-constructed homes, so as to achieve greater confidence in trends.

Utility data. We propose to examine high quality regional energy-related data sets and assess their suitability as supplements to RECS (and NBECS). Such data sets could add two new dimensions to both of the EIA surveys. They provide physical characteristics of the buildings measured by an auditor on-site (in contrast to the EIA mail surveys). Previously unavailable data would include more accurate floor areas, measured equipment efficiencies, insulation levels, and occupancy schedules. Second, the regional data sets often contain monitored data for several end uses and at frequent intervals. Many large utilities have conducted extensive and detailed energy audits, surveys, and monitoring programs. In some cases, the samples were selected with statistical rigor similar to that of RECS or NBECS. The data could provide valuable baseline energy-use and building characteristics which could permit more accurate nationwide extrapolations. The nationwide relevance increases rapidly as these studies are linked. The first candidate might be the utility users of the ARM monitoring equipment. The ARM is a standard monitoring package, developed by the Electric Power Research Institute, and being used by several utilities across the U.S.

Other sources. NAHB, Dodge, and other groups collect data that could provide more detail about the existing stock and new construction trends. Such data might improve the quality of the adjustments. For example, NAHB collects more detailed information on characteristics of newly constructed houses than the US Census' *Characteristics of New Housing*, but charges a fee to generate aggregations not already published. We have not used these sources (beyond what they publish) owing to the high access costs.

REFERENCES

Goldman, C.A., K.M. Greely, J.P. Harris,"Retrofit Experience in U.S. Multifamily Buildings: Energy Savings, Costs and Economics," Lawrence Berkeley Laboratory Report No. LBL-25248, May 1988.

McMahon, J., "The LBL Residential Energy Model: An Improved Policy Analysis Tool," Lawrence Berkeley Laboratory Report No. LBL-18622, 1985.

Meier, A., B. Nordman, C. Conner and J. Busch, "A Thermal Analysis of Homes in Bonneville Power Administration's Residential Standards Demonstration Program," Lawrence Berkeley Laboratory Report No. LBL-22109, September 1986.

Meier, A. et al., "Testing the Accuracy of a Measurement-Based Building Energy Model with Synthetic Data," *Energy and Buildings* (in press).

Meyers, S., "Energy Consumption and Structure of the U.S. Residential Sector: Changes Between 1970 and 1984," Lawrence Berkeley Laboratory Report No. LBL-21190, March 1986.

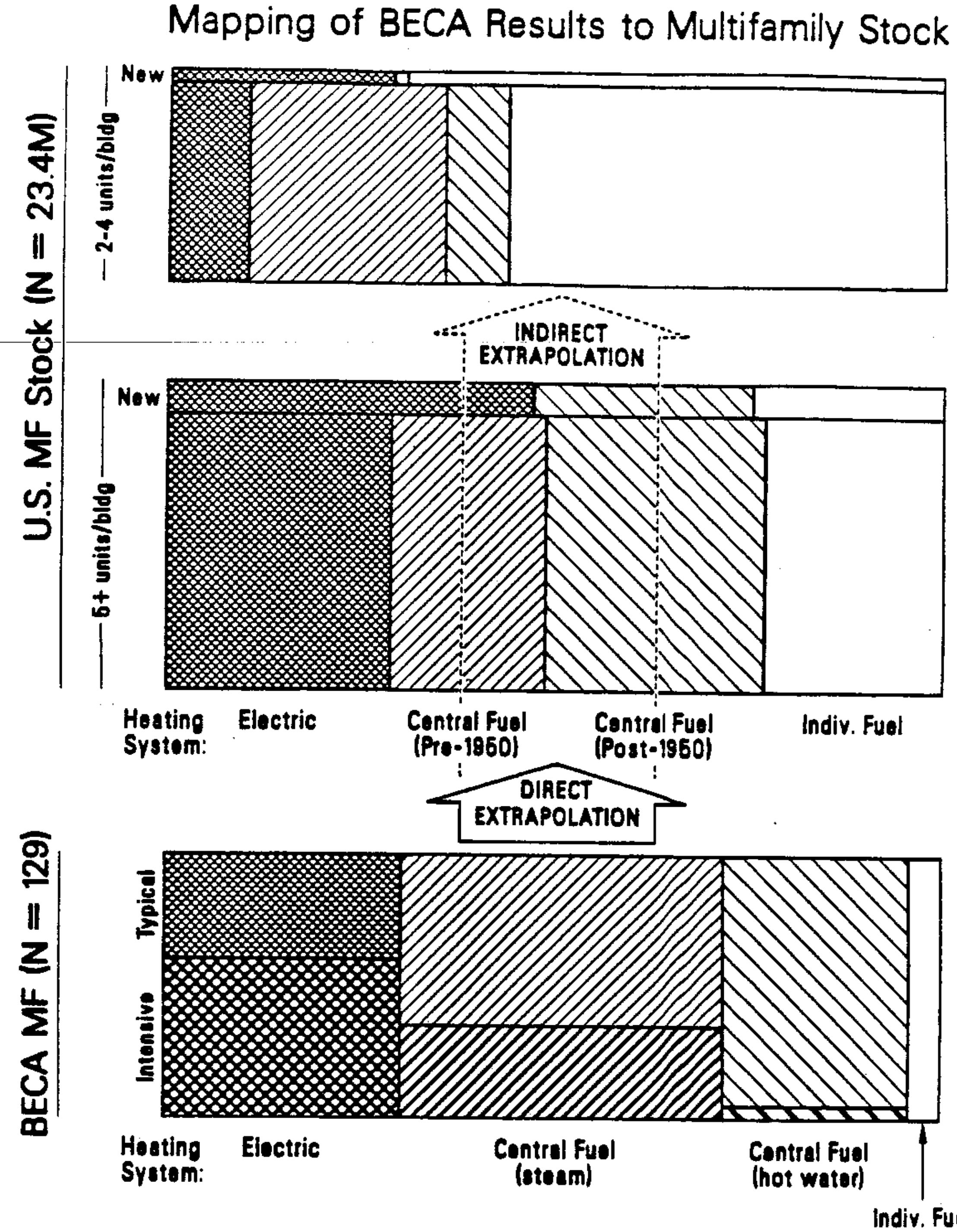

Figure 1. Mapping of the *direct* and *indirect* extrapolation of savings from groups of BECA multifamily buildings to the multifamily stock. For the U.S. multifamily stock, the vertical scale is proportioned by the relative number of existing and new (i.e., post-1980) apartment units in small and large multifamily buildings (i.e., 2-4 units and 5+ units). The horizontal scale is scaled by the number of electric heat, central fuel heat, and individual-fuel heat apartment units. The BECA-MF groups are proportioned by the number of "typical" and "intensive" retrofit projects and by heating system and fuel type. Note that stock data on the type of heating distribution system for buildings with central heating (i.e. steam versus hot water) are not available from RECS, so we have assumed that centrally heated buildings built before 1950 have steam distribution systems, and that centrally-heated buildings constructed after 1950 have hot water distribution systems.

Annual Energy Savings as Extrapolated from BECA-MF to Multifamily Stock:

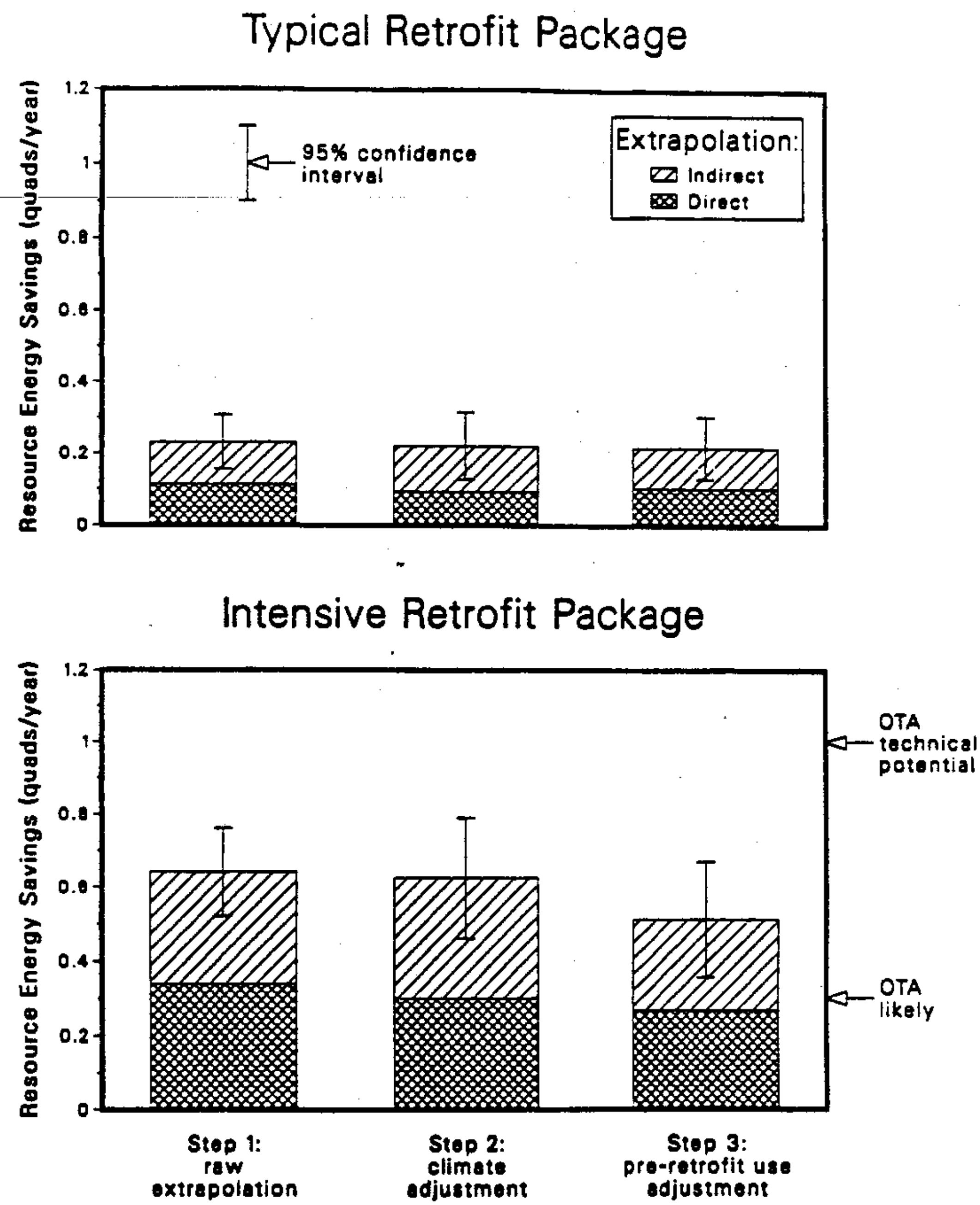

Figure 2. Raw and adjusted nationwide estimates of savings potential are shown for typical and intensive retrofit packages. "Direct" extrapolation refers to the savings potential for 5+ unit buildings; savings for 2-4 unit buildings are shown as "indirect" extrapolation. Error bars show 95% confidence interval of savings estimate, typically about ±40% of the mean value (see Appendix A for discussion of uncertainty analysis). Table A-5 describes the adjustments shown here in more detail. Estimated technical and likely conservation potential are shown for comparison from a 1982 study performed by the Office of Technology Assessment (OTA).

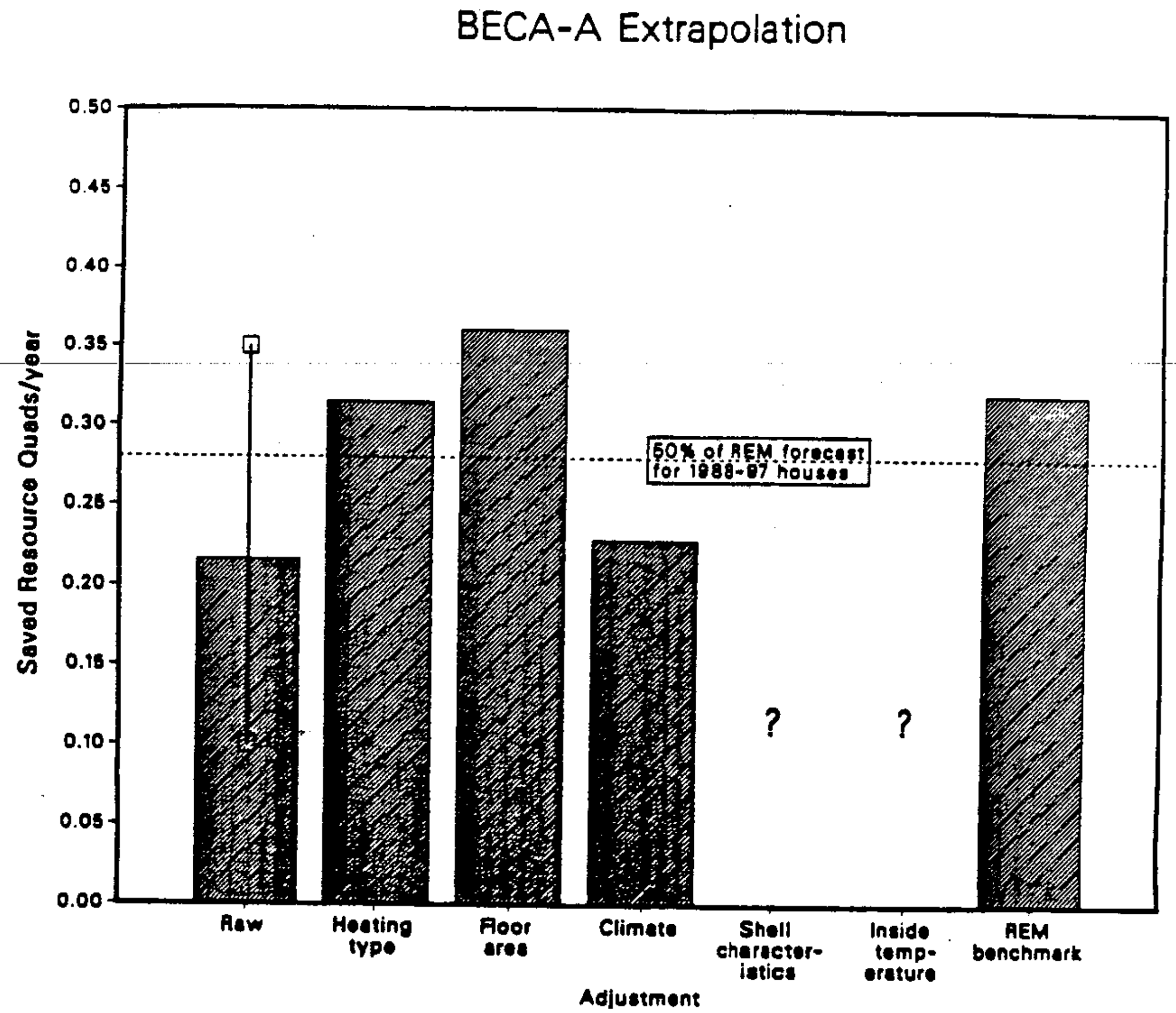

Figure 3. Stockwide savings for new, electrically-heated houses (1988-97) based on BECA-A extrapolation. Each bar represents the change in the estimate due to the inclusion of another adjustment. The "raw" extrapolation is the multiplication of the RSDP savings by the stock of homes to be built between 1988-97. The standard deviations of the original RSDP savings have been superimposed to indicate the *minimum* range of uncertainty in this estimate. The dashed, horizontal line represents 50% of the energy use which REM predicted would be used by these houses. The two adjustments noted with question marks could be performed in a future study, as better data are collected.

Appendix A

EXISTING MULTIFAMILY BUILDINGS EXTRAPOLATION

Background

This extrapolation considers the energy savings in existing multifamily buildings. The extrapolation relies on two kinds of data. First, the BECA database provides measured energy savings from retrofits of multifamily buildings. Second, this information is used in conjunction with the energy usage patterns, heating system type, floor area, and climatic location of the multifamily stock to assess the savings potential that can be achieved based on current conservation program experience.

Data Sources

The BECA Multifamily (MF) database currently includes over 200 U.S. retrofit projects, representing 20,000 apartment units (Goldman et al., 1988). Information on retrofit projects is obtained from several sources, including city energy offices [70], public housing authorities [38], research institutions and national laboratories [17], non-profit and for-profit energy service companies [36], and utilities [39].[1] In most cases, each data point represents one building, except in the case of public housing projects, which often have a number of buildings on one utility master meter. Almost all multifamily buildings in the BECA database have five or more units. Retrofit efforts focused on reducing space and domestic hot water heating energy. Most of the fuel-heat buildings have central heating systems, while individual unit baseboard electric heating predominates in the "all-electric" buildings. In addition, measured energy consumption data come principally from utility bills, and thus typically include all end uses of the space heat fuel.[2]

Stock Energy Use and Building Characteristics

We used the 1984 Residential Energy Consumption Survey (RECS) for information on the existing multifamily stock (EIA 1987). RECS is a statistically representative sample of U.S. homes which surveys households on building and demographic characteristics and collects measured energy consumption data, typically in the form of utility bills. Climatic location, building size, heating system type, heating fuel, and vintage strongly influence energy consumption patterns in the 23 million multifamily apartment units (see Tables A-1 and A-2). For example, fuel consumption is about 20-30% higher in buildings constructed prior to 1950 compared to buildings built between 1950-80, even after correcting for floor area. Fuel and electricity consumption are significantly lower in newly-constructed multifamily buildings (i.e., post-1980) compared to the existing, older stock.

Several points should be made regarding energy consumption data in RECS. First, annual energy usage is not adjusted for the effects of weather (i.e., normalized to long-term weather conditions). However, we were able to apply weather-correction factors to the median consumption values for each category (i.e., fuel-heat buildings built prior to 1950) using long-term average heating-degree day data specially compiled for us by Energy Information Administration (EIA).[3] Weather-normalized fuel and electricity consumption, actual and long-term heating degree-days, and the assumed space heat fraction of the unit's energy consumption (UEC) are shown in Tables A-3 and A-4 for each building category.

[1] Numbers in brackets represent number of data points obtained from each source.

[2] For fuel-heated buildings, typical end uses include space heat, hot water, and in some cases cooking. Electric-heat buildings are typically "all-electric", thus all end uses are included.

[3] The estimated space heat fraction of total consumption for each group was scaled by the ratio of long-term HDD to actual year HDD to derive weather-corrected consumption. Long-term average weather data is not included in the published RECS documents and computer tapes, as it could be used to identify individual households.

Except for individually-heated fuel buildings, actual weather during this period (1984-85) tended to be slightly milder than long-term weather conditions, thus weather-normalized consumption was about 1-2% higher than raw consumption. Second, larger multifamily buildings typically do not have usable energy consumption records, and thus consumption is imputed from single-family buildings with similar characteristics. In essence, consumption for all master-metered buildings is imputed. For example, 53% of the natural gas records were usable in buildings with 2-4 units, however, this figure drops to only 18% in buildings with five or more units.[4]

The Extrapolation

Table A-5 summarizes the major steps used to extrapolate savings from multifamily buildings in the BECA database to the U.S. multifamily stock.

Step 1: Segment BECA-B multifamily data: First, we grouped BECA MF buildings on the basis of "typical" and "intensive" retrofit packages that were installed in key building and heating system types. Major market segments included: 1) central fuel heat buildings with steam heat distribution systems, 2) central fuel heat buildings with hot water distribution systems, 3) fuel-heat buildings with individual apartment unit space heaters, and 4) electric resistance-heated buildings. These market segments were chosen because they reflect key physical characteristics that affect savings potential and/or differing retrofit strategies. For example, retrofit efforts in central fuel heat buildings typically include various heating and hot water system measures, measures which for the most part are not applicable in electric heat buildings.

Median savings for typical retrofit efforts in fuel-heat buildings with central heating systems ranged between 6 and 18 kBtu/ft^2, about 13-15% of pre-retrofit fuel usage (Figure A-1). More intensive retrofits in these two groups yielded savings of about 45-50 kBtu/ft^2 and included more expensive heating system retrofits or shell measures (see Table A-6, Groups 1 and 2). Median savings were about 35% of pre-retrofit energy consumption. For fuel-heat buildings with individual unit heating, typical savings were 10 kBtu/ft^2 (or about 10% of pre-retrofit fuel consumption), although our sample is relatively small. Finally, median electricity savings were about 10% for individually-heated, electric baseboard, buildings that installed typical retrofits, while savings were 19% for intensively retrofit buildings in this group.[5] In these buildings, various shell measures were popular (additional glazing, insulation of attic and floor, caulking and weatherstripping) as well as a few low-cost hot water measures.

Step 2: Extrapolate BECA data to stock of 5+ unit buildings: We next extrapolated the measured savings from typical and intensive retrofit efforts in the four groups of BECA MF buildings to the stock of buildings with five or more units. This was done by multiplying energy savings/ft^2 (in resource terms) for each category by the total conditioned floor area for that group as reported in the 1984 RECS survey. Because information is not available in RECS on conservation measures already installed in larger multifamily buildings, we assumed that most buildings constructed after 1980 were not eligible for retrofits. This assumption captures the effect of more energy-efficient design standards included in recent building codes. However, the typical retrofit package was included only for central-heated fuel buildings on the basis that it was likely that heating system performance could be improved. This crude extrapolation yielded national savings of between 0.11 and 0.34 quads (in resource energy) for typical and intensive retrofits in multifamily buildings with five or more units.[6]

[4] See Table A-13. The largest cause of unusable records is the fact that fuel use is included in rent or paid in other ways (i.e., master-metered buildings), because RECS obtains consumption data for households that paid their own bills directly.

[5] Note that the 39 all-electric multifamily buildings are almost all located in the Pacific Northwest.

[6] Savings for all multifamily buildings (including 2-4 unit buildings) were 0.23 and 0.64 quads for typical and intensive retrofits.

Step 3: Adjust for climate zone differences (BECA vs stock): We then adjusted the crude stock savings estimates for the effect of differing climatic location between BECA MF buildings and the stock of multifamily buildings. We multiplied the estimated space heat fraction of savings for each market segment by the ratio of long-term average HDD in the stock to that in BECA-B. This adjustment is important because BECA MF buildings tend to be located in more severe heating climates, except for fuel-heat buildings with individual apartment unit space heaters (see Figure A-2).[7] If all other factors remain unchanged, this adjustment tended to reduce our estimate of savings potential in the stock.

Step 4: Scale savings for difference in pre-retrofit energy intensity: Step four in the analysis consisted of adjusting the climate-adjusted stock savings estimate for differences in initial pre-retrofit consumption (or unit energy consumption, UEC) that still remained between the stock of MF buildings and the BECA MF buildings.[8] Again, BECA MF buildings tend to have higher pre-retrofit energy consumption (even after adjusting for climatic differences) than RECS values for the multifamily stock. This trend was more pronounced for BECA MF buildings that received intensive retrofit packages. For example, stock savings for all multifamily buildings dropped from about 0.62 quads to 0.51 quads after this adjustment (see Figure 2).

Step 5: "Indirect" extrapolation to smaller buildings (2-4 units): The savings estimates for larger buildings are based on *direct* extrapolation, while estimates for smaller buildings - for which there are no BECA data - are *indirect*. In our base case, we assumed that median savings/ft^2 for larger multifamily buildings apply equally as well to 2-4 unit buildings with similar characteristics. We extrapolated to the stock using 1984 RECS data on energy use, conditioned area, and HDD of 2-4 unit buildings, repeating steps two to four. This assumption is reasonable for some of the smaller building market segments, particularly those buildings with central heating systems. Similar retrofit strategies are appropriate in these buildings (e.g., improved heating controls, system retrofits, less emphasis on shell), although the economics will not be as favorable because the cost to retrofit heating systems often have large economies of scale (e.g., costs to retrofit heating systems are approximately the same for one building regardless of the number of units). However, this assumption is less plausible for smaller buildings with gas and electric individual unit heaters. The physical and demographic characteristics of these buildings (i.e., shell-dominated, larger floor area per unit, fewer renters) coupled with choice of retrofit strategies (e.g., increased importance of envelope retrofits, fewer system retrofit options) means that national stock savings estimates can also be drawn from single-family retrofit experience. We performed a sensitivity analysis in which we extrapolated savings in individually heated fuel and electric buildings with 2-4 units based on measured data from typical retrofits in single-family buildings (see Table A-7). The climate- and UEC-adjusted savings potential from typical retrofits increased by 0.06 quads, to 0.28 quads for the multifamily stock. In percentage terms, the increase in stock savings potential is quite significant, about 30% higher than the basecase. Energy consumption decreased by over 20% in the single-family programs used in this analysis. This is double the percentage savings in large multifamily buildings. These market segments are important fractions in the stock (i.e., about six million units, accounting for 27% of the total multifamily stock); thus obtaining direct evidence of retrofit results for these sectors would improve our confidence in the extrapolation.

Summary: After adjusting for differences in climate and initial pre-retrofit consumption between BECA MF buildings and the U.S. multifamily stock, typical retrofits of U.S. multifamily buildings could save about 0.2 Quads per year (in resource energy), while intensive retrofits could save about 0.5 Quads per year (see Figure 2). These results suggest that current energy consumption in the multifamily sector could easily be reduced by 9-22% based on documented results from existing conservation programs.[9] It

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[7] Note that the climate adjustment is just for heating, because we have no data on cooling retrofits (a major gap in the analysis, particularly for buildings located in mild climates).

[8] Note that the average UEC for BECA MF buildings was first adjusted for climate differences from the stock.

[9] This number is calculated by taking the stock savings estimate for typical and intensive retrofits divided by the energy consumption of the main heating fuel for all multifamily buildings (2.38 quads in resource energy). This approach is quite conserva-

is also interesting to see how our preliminary extrapolation compares with other studies of conservation potential in the multifamily sector. A 1982 OTA study concluded that the technical potential for energy conservation in multifamily buildings was about one quad/per year by 2000, although likely savings were only estimated at about 0.3 quads because of various institutional, financial and technical barriers (OTA 1982).

Uncertainty in the Savings

Uncertainty arises in every step of an extrapolation of this kind. Some of these sources, such as the uncertainty in different numerical quantities, can be quantified in the form of standard errors. Others, such as the correctness of assuming that savings in 5+ unit buildings apply equal well to 2-4 unit buildings, cannot. As a check of our *assumptions*, we compared the measured savings from retrofitted multifamily buildings in the BECA database with retrofit performance in single family houses (where appropriate), and with engineering estimates of the multifamily sector's savings potential. These comparisons were discussed in the previous section; they show that the extrapolation results are within the range of savings bracketed by other estimates. As a check of the *quantifiable uncertainty*, we combined the numerical uncertainties in the savings estimates and the extrapolation adjustments to obtain the standard error of the final estimate of savings potential. This analysis is useful because it clarifies which factors are the most important contributors to the uncertainty in the stock extrapolation savings estimates.

We calculated standard errors for all parameters used in the adjustments, including the initial BECA savings for each category, the RECS floor area, the pre-retrofit consumption and heating degree-days from both BECA and RECS. In addition, we estimated the relative uncertainty of the assumed space heat fraction of total consumption and energy savings (about 15-20%). Using this information, we calculated the standard error in the savings potential at each step of the extrapolation process. Our analysis of the uncertainty in the climate- and UEC-adjusted stock savings estimates indicate that the 95% confidence interval for savings from the typical retrofit package is 0.2 ±0.09 quads/year, and 0.5 ±0.2 quads/year for the intensive retrofit package. This analysis of quantifiable uncertainty indicates how well determined the results of the extrapolation are, given that our assumptions about how to extrapolate results from the BECA database to the stock are correct (i.e., we have not left out any significant adjustments, such as corrections for indoor temperatures, occupant behavior, etc.).

In both the typical and intensive retrofit savings calculations, the BECA energy savings are the largest source of error among the included variables (relative standard error for typical retrofits=25-50%, for intensive retrofits=20-25%). Surprisingly, the RECS estimates of floor area are the second largest source of error in both extrapolations, with relative standard errors of 8-30%. Therefore, most of the uncertainty occurs in step one, reflecting the large variability in both these estimates. For example, in the estimated savings potential for intensively retrofit buildings, the relative standard errors increase from 9% in step one to 13% in step two to 15% in step three. Improving the certainty in our stock savings estimates would require improved BECA coverage of each market segment (more diversity in retrofit type, building characteristics, and regional location), as well as over-sampling of multifamily households in RECS to obtain more reliable estimates of floor area.[10]

tive, because the main heating fuel includes other end uses in almost all households. The percent reduction in space heating is much higher, but difficult to estimate with only utility billing data.

[10] Relative standard errors in RECS are typically a function of the number of households in a particular sub-group. For example, RECS values on average energy consumption of the 82 million U.S. households are much better determined than the consumption values given for the five million multifamily households that have individual apartment unit heaters.

Costs of the Measures

We estimated the cost of retrofitting the entire multifamily stock by applying retrofit cost data from BECA MF buildings that installed "typical" and "intensive" retrofit packages. Typical retrofits ranged from $50-180/apartment in fuel-heated buildings, while intensive retrofits cost about $1000/apartment. Payback times were close to two years for the typical measures and about five years for the intensive measures (costs of conserved energy of $2/MBtu and $4/MBtu, respectively). In electrically heated buildings, payback times were over 20 years for both the typical and intensive retrofits (cost of conserved energy of $8-11/resource MBtu); initial costs were $1300/apartment for the typical package and $2400/apartment for the intensive package.

Different bases for extrapolating costs to the national stock are required for different kinds of retrofits. For instance, costs for insulation scale with floor area, while costs to install low-flow showerheads scale with the number of apartments, and costs to retrofit heating systems are approximately the same for one building, regardless of the number of units. To bracket the range in stock retrofit costs, we extrapolated BECA costs by apartment and by floor area. Because BECA buildings are generally larger and older than the stock average, we also introduced a "building size" factor into the extrapolation of heating system retrofit costs.[11]

Based on these adjustments for retrofit type, costs for retrofitting the entire multifamily stock range between $7.5-11 billion for typical retrofits to $27-32 billion for intensive retrofits (1987 $). Retrofitting the 5+ unit stock only would cost $4.7-5.8 billion with typical measures, and $17-18 billion with intensive measures.

REFERENCES

Goldman, C.A., K.M. Greely, J.P. Harris, "Retrofit Experience in U.S. Multifamily Buildings: Energy Savings, Costs and Economics," Lawrence Berkeley Laboratory Report No. LBL-25248, May 1988.

Energy Information Administration, "Residential Energy Consumption Survey: Consumption and Expenditures, April 1984 through March 1985," DOE/EIA-0321/1 (1987).

Office of Technology Assessment (OTA), "Energy Efficiency of Buildings in Cities," OTA-E-168, Washington DC, 1982.

[11] BECA buildings have the same to twice as many units per building as the average 5+ unit centrally heated fuel buildings in RECS, and 6-8 times as many as the RECS 2-4 unit buildings (the low end of the range represents buildings with steam distribution, and the high end, buildings with water distribution).

Table A-1.
U.S. Multifamily Stock: Buildings with 5 or more units
(1984 Residential Energy Consumption Survey)

Category	No. of Units	Fuel Use (MBtu/apt)	Fuel Use (kBtu/sqft)	Site Elec. Use (MBtu/apt)	Site Elec. Use (kBtu/sqft)	Region (%) N.East	Region (%) N.Central	Region (%) South	Region (%) West	Climate Zone (%) 1	Climate Zone (%) 2	Climate Zone (%) 3	Climate Zone (%) 4
All	13,430,935					27	23	26	24	14	24	22	40
Fuel space heat, built before 1950 (central heating)	2,427,164	81.6 ± 5.3	132.5 ± 11.4	6.2 ± 0.4	11.7 ± 1.0	73	13	6	8	10	30	44	16
Fuel space heat, built from 1950-1980 (central heating)	3,458,441	82.7 ± 4.5	103.3 ± 7.4	8.8 ± 0.5	12.1 ± 0.9	27	49	11	13	28	35	24	13
Fuel space heat, built after 1980 (central heating)	326,175	61.5 ± 9.9	91.9 ± 19.1	8.3 ± 1.1	13.4 ± 2.6	28	72	0	0	30	64	6	0
Fuel space heat, built before 1980 (individual heating)	2,742,029	49.3 ± 3.0	62.0 ± 5.0	13.3 ± 0.9	15.5 ± 1.3	8	22	28	42	14	15	15	56
Fuel space heat, built after 1980 (individual heating)	286,510	39.7 ± 6.6	57.1 ± 12.3	12.4 ± 1.8	14.7 ± 2.9	2	14	4	80	6	9	35	50
Elec. space heat, built before 1980	3,546,342	0	0	31.2 ± 1.8	38.6 ± 2.9	15	6	49	30	6	15	14	65
Elec. space heat, built after 1980	556,191	0	0	24.9 ± 2.8	35.6 ± 5.5	0	0	88	12	0	3	8	89

Table A-2.
U.S. Multifamily Stock: Buildings with 2 to 4 units
(1984 Residential Energy Consumption Survey)

Category	No. of Units	Fuel Use (MBtu/apt)	Fuel Use (kBtu/sqft)	Site Elec. Use (MBtu/apt)	Site Elec. Use (kBtu/sqft)	Region (%) N.East	Region (%) N.Central	Region (%) South	Region (%) West	Climate Zone (%) 1	Climate Zone (%) 2	Climate Zone (%) 3	Climate Zone (%) 4
All	9,968,798					32	28	17	23	13	31	24	32
Fuel space heat, built before 1950 (central heating)	2,299,688	100.2 ± 6.6	122.8 ± 10.7	10.4 ± 0.7	11.9 ± 1.1	62	34	3	1	12	42	38	8
Fuel space heat, built from 1950-1980 (central heating)	819,569	78.7 ± 8.3	82.7 ± 11.4	9.4 ± 0.9	10.2 ± 1.4	39	48	7	6	29	35	32	4
Fuel space heat, built after 1980 (central heating)	7,523 *												
Fuel space heat, built before 1980 (individual heating)	5,244,026	78.9 ± 3.6	73.0 ± 4.4	13.4 ± 0.7	12.9 ± 0.9	26	27	21	26	13	30	19	38
Fuel space heat, built after 1980 (individual heating)	297,841	36.9 ± 6.0	48.5 ± 10.3	18.4 ± 2.6	18.2 ± 3.6	2	13	9	76	15	0	0	85
Elec. space heat, built before 1980	903,545	0	0	34.7 ± 3.3	42.8 ± 5.5	2	15	39	44	7	22	15	56
Elec. space heat, built after 1980	119,284	0	0	28.7 ± 5.5	30.0 ± 8.4	4	0	49	47	0	9	26	65

* Sample too small to calculate energy usage for this group.

Table A-3.
Correction Factors applied to U.S. Multifamily Stock: Buildings with 5 or more units
(1984 Residential Energy Consumption Survey)

Category	No. of Units	Cond.Area (sqft)	Cond.Area (sqft/apt)	HDD(base 65°F) 1984	HDD(base 65°F) LTA	Space Heat % of UEC †	Normalized Fuel (MBtu/apt)	Normalized Fuel (kBtu/sqft)	Normalized Site Elec. (MBtu/apt)	Normalized Site Elec. (kBtu/sqft)
All	13,430,935	10,740,000,000								
Fuel space heat, built before 1950 (central heating)	2,427,164	1,684,696,130 ± 202,080,000	588 ± 33	5295 ± 207	5372 ± 148	74	82.5 ± 5.4	133.9 ± 11.5	-	-
Fuel space heat, built from 1950-1980 (central heating)	3,458,441	2,723,867,287 ± 277,740,000	753 ± 36	6008 ± 144	6105 ± 237	75	83.7 ± 4.5	104.6 ± 7.5	-	-
Fuel space heat, built after 1980 (central heating)	326,175	213,745,872 ± 64,337,245	641 ± 85	6627 ± 338	6537 ± NA	77	62.2 ± 10.0	93.0 ± 19.3	-	-
Fuel space heat, built before 1980 (individual heating)	2,742,029	2,417,891,725 ± 275,530,000	799 ± 42	4045 ± 287	4016 ± 319	67	49.1 ± 3.0	61.7 ± 4.9	-	-
Fuel space heat, built after 1980 (individual heating)	286,510	238,853,622 ± 76,194,107	724 ± 101	3953 ± 518	4771 ± 1142	68	45.3 ± 7.5	65.2 ± 14.1	-	-
Elec. space heat, built before 1980	3,546,342	3,061,867,016 ± 309,160,000	800 ± 38	3390 ± 244	3499 ± 424	30	-	-	31.5 ± 1.9	39.0 ± 3.0
Elec. space heat, built after 1980	556,191	400,641,179 ± 94,551,276	700 ± 74	2598 ± 447	2752 ± 794	23	-	-	25.2 ± 2.9	36.0 ± 5.6

† From RECS 1982 end-use estimates.

Table A-4.
Correction Factors applied to U.S. Multifamily Stock: Buildings with 2 to 4 units
(1984 Residential Energy Consumption Survey)

Category	No. of Units	Cond.Area (sqft)	Cond.Area (sqft/apt)	HDD(base 65°F) 1984	HDD(base 65°F) LTA	Space Heat % of UEC †	Normalized Fuel (MBtu/apt)	Normalized Fuel (kBtu/sqft)	Normalized Site Elec. (MBtu/apt)	Normalized Site Elec. (kBtu/sqft)
All	9,968,798	10,630,000,000								
Fuel space heat, built before 1950 (central heating)	2,299,688	2,317,288,022 ± 284,990,000	754 ± 43	5662 ± 198	5778 ± 91	76	101.8 ± 6.7	124.7 ± 10.9	-	-
Fuel space heat, built from 1950-1980 (central heating)	819,569	880,731,082 ± 174,380,000	800 ± 71	6127 ± 294	5959 ± 190	76	77.1 ± 8.2	81.0 ± 11.2	-	-
Fuel space heat, built after 1980 (central heating)	7,523 *	5,740,049 ± 9,402,200	763 ± 488							
Fuel space heat, built before 1980 (individual heating)	5,244,026	5,972,761,885 ± 507,620,000	938 ± 38	4842 ± 160	4751 ± 160	70	77.9 ± 3.5	72.1 ± 4.3	-	-
Fuel space heat, built after 1980 (individual heating)	297,841	310,698,023 ± 97,559,172	991 ± 136	3770 ± 633	4213 ± 1312	61	39.5 ± 6.4	51.9 ± 11.1	-	-
Elec. space heat, built before 1980	903,545	791,648,131 ± 149,620,000	840 ± 72	3971 ± 365	4059 ± 270	33	-	-	35.0 ± 3.3	43.2 ± 5.5
Elec. space heat, built after 1980	119,284	121,599,951 ± 58,002,723	997 ± 202	2557 ± 586	2963 ± NA	30	-	-	30.1 ± 5.8	31.5 ± 8.8

* Sample too small to calculate energy usage for this group.

† From RECS 1982 end-use estimates.

Table A-5: Summary of BECA-B Multifamily Extrapolation Method

Step 1: Segment the BECA-B multifamily data.

Approach: Subdivide BECA data into:

- "Typical" retrofits: market conditions; 10-15% savings; costs = $50-200/apartment for fuel-heated buildings, $1300/apartment for buildings with electric space heat.
- "Intensive" retrofits: government/utility subsidies; 20-35% savings; costs = $800-1100/apartment in fuel-heat buildings, $2400/apartment in electric-heat buildings.

Results: Median annual savings of space heat fuel (normalized to local average HDD), costs, and payback times, for 5+ unit buildings in BECA, for 4 space heat fuel and system types.

Refer to: Figure A-1; Table A-6.

Step 2: Extrapolate segmented BECA data to stock of 5+ unit buildings.

Approach: Extrapolate BECA savings/sq.ft. to the stock of 5+ unit buildings, using the total conditioned area of these buildings, as reported in Residential Energy Consumption Survey (RECS) 1984 public-use tape.[1]

Results: Initial estimate of savings for stock of 5+ unit buildings ("typical" and "intensive" packages, 4 space heat fuel and system types[2]).

Refer to: Figures 1, 2; Tables A-1, A-3.

Step 3: Adjust for climate zone differences (BECA *vs* stock).

Approach: Multiply the estimated space heat fraction of savings for each segment by the ratio of long-term average HDD (base 65° F) in the stock to that in BECA-B.[3]

Results: Climate-adjusted savings for 5+ unit buildings ("typical" and "intensive" packages, 4 space heat fuel and system types).

Refer to: Figures 2, A-2; Tables A-1, A-3.

Step 4: Scale savings for difference in pre-retrofit energy intensity.

Approach: Scale savings by the ratio of pre-retrofit energy/sq.ft. (unit energy consumption, or UEC) in the stock (normalized for long-term average HDD) to that of BECA-B (also HDD-normalized), for each fuel/system segment of 5+ unit buildings.

Results: Final, climate- and UEC-adjusted savings estimates for 5+ unit buildings.

Refer to: Figure 2; Tables A-1, A-3.

Step 5: "Indirect" extrapolation to smaller buildings (2-4 units).

Approach: Assume BECA-B average savings per square foot for 5+ unit buildings apply equally well to 2-4 unit buildings. Extrapolate as in Steps 2 through 4, using RECS 1984 tape information on energy use, conditioned area, and HDD of 2-4 unit buildings.[4]

Results: Final, climate- and UEC-adjusted savings estimates for 2-4 unit multifamily buildings.

Refer to: Figures 1, 2; Tables A-2, A-4.

Table A-5 Notes:

[1]We normalize for floor area because BECA-B apartments are typically bigger than the 5+ units/building stock average, and smaller than the 2-4 units/building stock average.

[2]Because RECS does not collect data on distribution system type, we assumed that centrally heated fuel buildings built prior to 1950 have steam distribution systems, while those built after 1950 use hot water distribution. Because no information is available in RECS regarding conservation measures already installed in the 5+ unit stock, we assumed that most buildings constructed since 1980 were not eligible for retrofitting, because of recent building codes requiring higher insulation levels. We applied the "typical" retrofit package to centrally heated fuel buildings only, as it is likely that their heating system efficiencies could be improved.

[3]Most of the BECA-B buildings are in cooler-than-average regions (see Figure A-2).

[4]This last step is defined as a "indirect" extrapolation, since BECA lacks direct data on retrofit results for smaller buildings.

Table A-6.
BECA-B Retrofitted Multifamily Buildings: Categories for extrapolation to U.S. stock †

Category	Package	No. of Projects	Cond. Area (sqft/apt)	HDD (base 65°F)	Pre-Retrofit Use (kBtu/sqft) *	Savings (kBtu/sqft) *	Cost (1987) (¢/sqft)	Cost (1987) ($/apt)	SPT (years)
Fuel space heat, centrally heated with steam	Typical[a]	35	830	8007	112 ± 8	18 ± 4	19 ± 5	170 ± 47	2.3 ± 0.7
	Intensive[b]	18	917	6478	157 ± 16	50 ± 10	103 ± 13	1084 ± 172	4.8 ± 1.2
Fuel space heat, centrally heated with hot water	Typical[c]	30	760	8159	85 ± 12	6 ± 3	7 ± 3	51 ± 22	1.2 ± 1.0
	Intensive[d]	2	601	8007	127 ± NA	45 ± NA	143 ± NA	873 ± NA	5.7 ± NA
Fuel space heat, individually heated	Typical[e] Intensive	5	863	3161	104 ± NA	10 ± NA	21 ± 7	181 ± 49	4.3 ± NA
Elec. space heat	Typical[f]	15	759	5185	40 ± 3	4 ± 2	121 ± 22	1278 ± 169	23.6 ± 34.1
	Intensive[g]	24	747	4691	46 ± 2	8 ± 2	278 ± 36	2382 ± 277	22.5 ± 7.5

† Values for energy use and retrofit costs are given as median ± standard error.

* Electricity use is converted to site MBtu using 1 kWh=3413 Btus.

[a] Includes heating system alterations, such as steam balancing, thermostatic radiator valves, reset and cutout controls, vent dampers, energy management systems, steam to hot water conversion for double-pipe steam buildings, furnace derating, tune-ups, turbolators, and flame retention head burners.

[b] Includes combinations of attic insulation or window treatments with heating system alterations.

[c] Includes reset and cutout controls, vent dampers, attic insulation, and heating system alterations (separate hot water heaters, front end boilers).

[d] Includes high-efficiency or front-end boilers, clock thermostats, attic insulation, and caulking/weatherstripping.

[e] In BECA-B, there are only two buildings in this category. Therefore, the comprehensive package for this category is based on savings from shell measures in centrally and individually heated buildings using fuel for space heat, as the type of heating system should not affect percentage savings from envelope measures. Absolute savings are scaled using pre-retrofit consumption for individually heated buildings.

[f] Includes insulation and window treatments.

[g] Includes more extensive insulation (attic, floor, and some wall), window and door treatments, and, in some cases, heat exchangers.

Table A-7.
BECA-B Retrofitted Single Family Buildings:
Categories for extrapolation to U.S. stock †

Category	Package	No. of Projects	No. of Houses	Cond. Area (sqft/apt)	HDD (base 65°F)	Pre-Retrofit Use (kBtu/sqft) *	Savings (kBtu/sqft) *	Cost (1985) (¢/sqft)	SPT (years)
Fuel Heat Research Studies[a]	Typical	11	44	1500	4872	73	20	88	7.4
Fuel Heat Insulation Programs[a]	Typical	6	33,216	1736	5894	76	11	31	5.4
Electric Utility Conservation Programs[b]	Typical	11	10,515	1444	5185	56	9	121	14

† Values for energy use and retrofit costs are given as medians.

* Electricity use is converted to site MBtu using 1 kWh=3413 Btus.

[a] This category corresponds to "Fuel space heat, individually heated" in the multifamily extrapolation for 2-4 unit buildings.

[b] This category corresponds to "Electric space heat" in the multifamily extrapolation for 2-4 unit buildings.

ENERGY SAVINGS & COST-EFFECTIVENESS OF RETROFITS IN BECA-MF BUILDINGS

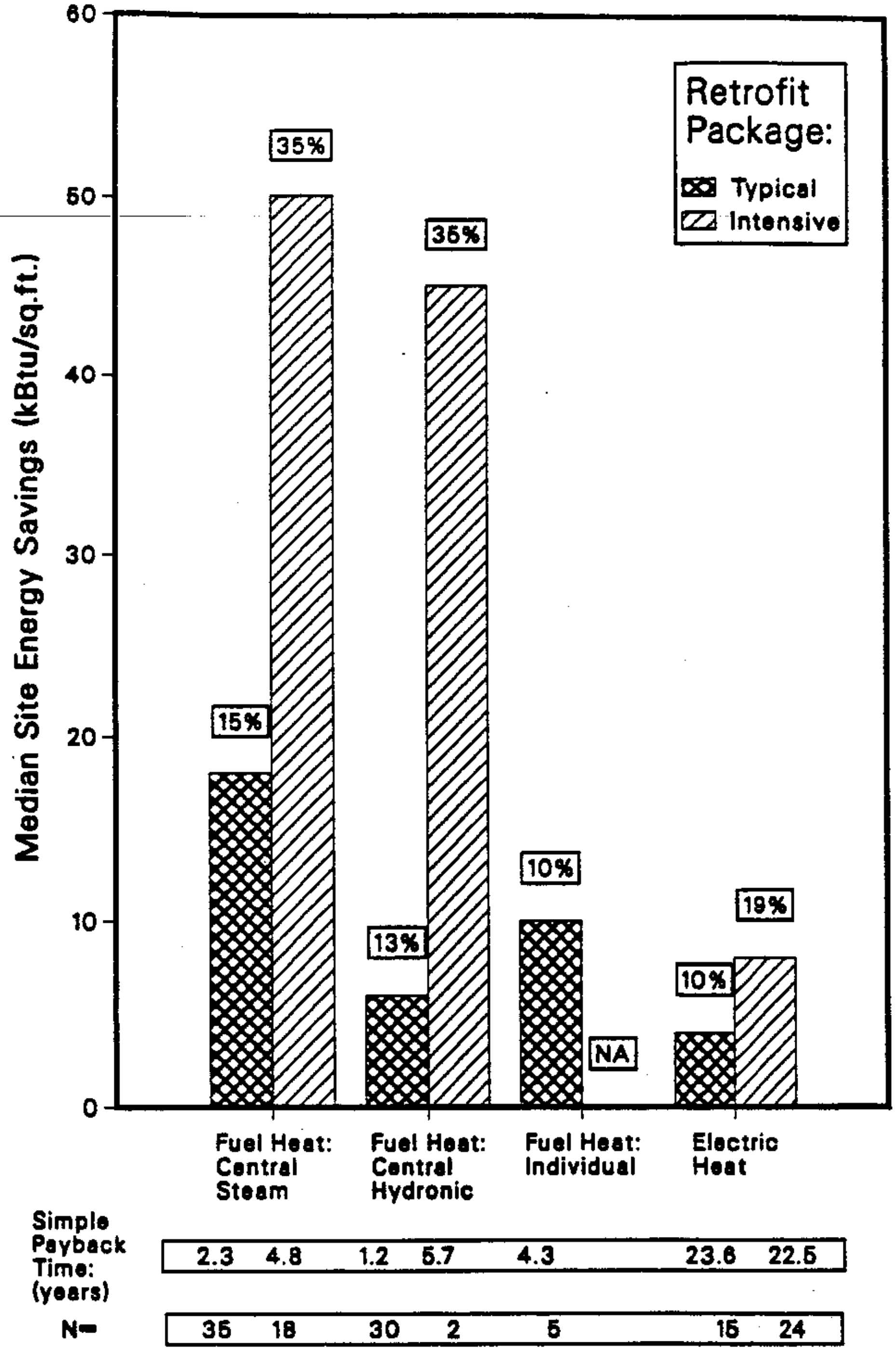

Figure A-1. Energy savings and cost-effectiveness of "typical" and "intensive" retrofits in multifamily buildings from the BECA database. "Typical" savings are from the documented performance of retrofits based on current market conditions, reflecting the investment criteria of building owners (i.e., 3 year payback time). "Intensive" savings are measured results of programs that use societal benefits as the investment criteria, and typically involve government or utility subsidy of the initial retrofit cost. The segmentation by heating system and fuel type reflect important differences in type and uniqueness of retrofit strategies and key physical characteristics that affect savings potential.

Climate Regions of BECA-MF Buildings vs. Multifamily Stock

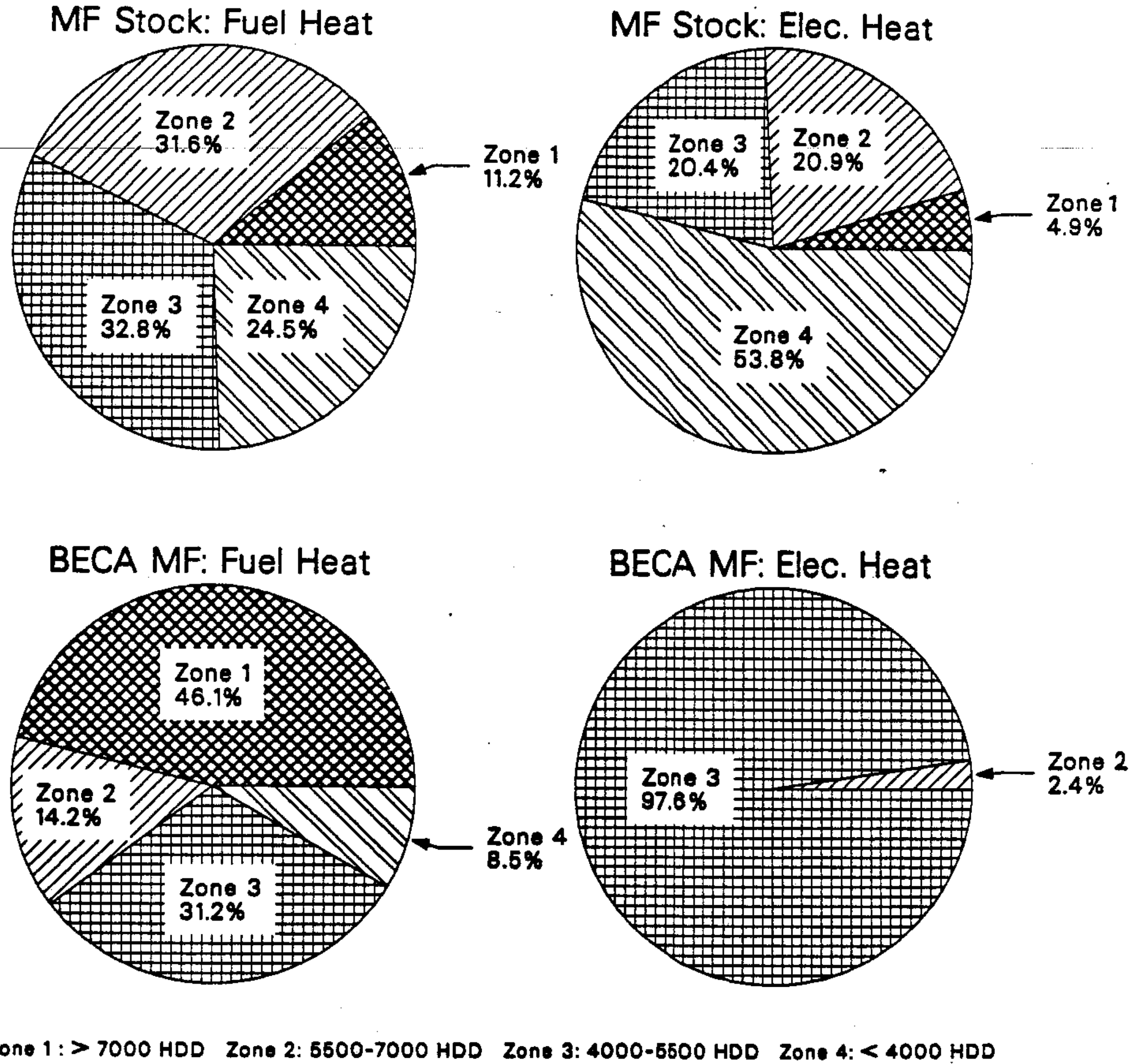

Figure A-2. Comparison of climate regions of BECA MF buildings with the multifamily stock. Step 2 in the adjustment process crudely corrects the stock savings estimate for these differences in climatic location. BECA contains no data on cooling retrofits, which would significantly affect savings estimates in mild climates.

Appendix B

NEW, ELECTRICALLY-HEATED SINGLE-FAMILY HOMES EXTRAPOLATION

Background

This extrapolation considers the technical potential for saving energy in new homes. The scenario is: *how much space heating electricity could be saved in the next decade through construction of more efficient houses based on demonstrated savings in the BECA compilation?* The problem is complicated by the fact that we do not know how much energy new houses will use or many houses will be built. As a result, the extrapolation relies on two kinds of data. First, BECA-A provides documentation of energy use for energy efficient residential construction. Ordinarily, we would need another source for baseline energy use data in order to determine the savings. To avoid inconsistencies, we chose a group of buildings in BECA-A that has its own baseline. Second, an estimate of housing stock is needed to calculate the nationwide savings. The LBL Residential Energy Model (REM) provides estimates of future construction rates. The current stocks in the model are periodically calibrated to the latest RECS, but the projections of electrically heated house construction rely on relative fuel prices, income, and thermal integrity of the shell (McMahon, 1985).[1]

Data Sources

BECA-A consists of over 800 energy-efficient homes constructed around the United States, Canada, and Europe. The houses monitored under the Residential Standards Demonstration Program (RSDP) is a major subset of the BECA-A data set (Meier et al., 1986). The Bonneville Power Administration (BPA) subsidized the design and construction of several hundred all-electric homes built to much higher thermal standards than current practice in the Northwest. It monitored these electrically-heated homes and an equal number of homes built to current practice. The heating systems included central electric furnace, baseboard, heat pumps, and radiant. All of the homes had separately metered furnaces and a data logger to collect inside and outside temperatures. The occupants recorded the meter readings every week and mailed them on a postcard to BPA.

LBL used the BECA-A analysis techniques to assess the energy saved. The results are particularly robust because the project covered a wide range of climates, construction techniques, and (all electric) heating equipment. Figure B-1 summarizes the space heating savings found in the RSDP.

The BPA project demonstrated that houses built with additional efficiency measures -- principally more insulation and less infiltration -- used about 45% less space heat than the Control houses. This corresponds roughly to an average of 2500 kWh/year. Even after adjusting for differences in inside temperatures and internal gains, however, a wide range in energy use and savings remained. The error bars in the figure indicate the range of use.

Baseline Energy and Building Characteristics

The unusual feature of the RSDP was that BPA selected an equally large control group, which was monitored to the same level of detail. In addition, BPA created "matched-pairs" of Model Conservation Standards (MCS) and Control houses, that is, houses of similar design built by the same contractor, but with different levels of insulation and conservation features.[2]

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[1] Since the fuel selection algorithm depends on the annual heating cost, the assumption of higher insulation levels would increase the rate of construction of electrically-heated homes. We did not include the effect; instead, we "froze" the stock projection presently used by REM.

[2] The excellent data base for the Northwest permitted us to cross-check the RECS baseline consumption. We first extracted the households in RECS that were located in the Pacific Northwest. We selected all households in the "Western" RECS survey region in climates having more than 4500 heating degree-days and less than 500 cooling degree-days. From that, we selected only those electrically-heated homes built during or after 1982. These criteria describe the Northwest, and the RSDP sample within it, quite accurately. The RECS projection for this group was based on a survey of about 10 houses. We compared the

The RSDP collected detailed descriptions of the MCS and Control homes, including component U-values, floor area, heating type, air leakage area, etc. For the MCS homes, the builders were asked to estimate the incremental cost of the measures needed to achieve the conservation standards.

Similar national data for new homes are less complete. NAHB publishes characteristics of new homes by region. This includes builders estimates of insulation levels, floor area, etc.[3] According to Meyers, the AHS data on heat pumps disagrees significantly with RECS data, but further comparisons are impossible because AHS is incomplete (Meyers, 1986). We used the REM breakdown — derived from RECS — because it is complete. A later census source indicates that in 1985 only 10% of the nation's electrically heated homes were built in the West region (which includes more than the Pacific Northwest) (U.S. Bureau of the Census, 1986). Thus the RSDP homes are a poor foundation for extrapolations to the entire stock because at least 90% of the new electrically-heated homes are being built elsewhere. The largest concentration — about two thirds — are being built in the South. With such a narrow basis for extrapolation, the energy and key thermal characteristics must be well defined so as to make appropriate adjustments.

The Extrapolation

The numeraire for the single-family extrapolation is the house. Floor area could have been used, but there appeared to be more confidence in the stock estimates than in the floor area estimates. Results of each adjustment are shown in Figure 3. The procedures for each adjustment are summarized in Table B-3.

The raw extrapolation. The simplest extrapolation is simply the product of the savings per house (determined from BECA-A) and the number of houses projected to be built between 1988 and 1997. This is the "raw extrapolation", and amounts to 0.22 Quads/year (resource energy) For the purposes of comparison, these savings represents about 45% of the 0.47 Quads/year that REM projects will be used by those new houses. The raw extrapolation implies that the average new electrically heated house will use about 9100 kWh/year for space heating.

Clearly, there are many uncertainties in such an extrapolation. The confidence intervals are difficult to calculate. The uncertainty originating from the RSDP data has been transferred to the figure, but the true uncertainty is obviously much greater. Another uncertainty is the number of electrically-heated houses built in the next decade; this could easily be half the number assumed in REM. As a result, all values have been rounded to two significant digits. Nevertheless, the raw extrapolation indicates the approximate size of the nationwide savings based on tangible experiments.

We then adjusted the results to reflect the differences between the U.S. and the conditions in the Northwest. Wherever possible, REM data were used. Other data bases, such as AHS, could be substituted for greater precision or to perform regional extrapolations. In any event, only REM provides *projections.*

Heating System Adjustment. In the RSDP, the type of heating system (central furnace, heat pump, and radiant) greatly affected the energy savings (see Figure B-2). The MCS savings for houses with forced air systems was over twice that for heat pumps (5200 kWh vs. 1900 kWh). The percentage savings for all heating system types were similar, but the Control houses with heat pumps had a much lower baseline; hence the lower absolute savings. In any event, the mix of heating types clearly affects the nationwide

average total electricity use in the RECS subsample to that in the 200+ Control homes in RSDP. The RECS homes used about 20% more electricity than the Control homes (25,000 versus 21,000 kWh per year). (The RSDP value is about one standard deviation from the RECS prediction.) It suggests — but does not prove — that RECS overestimates total electricity use. It is then possible that its prediction of space heating might be similarly high. Other factors could also explain the difference, such as the Control homes being more efficient than the stock average.

[3] The data are published for all heating types, and crosstabs can only be obtained by special order from NAHB Research Foundation.

savings.

REM projected the numbers of homes using different heating types. This permitted us to adjust the extrapolated savings to reflect the nationwide patterns in heating systems. In other words, we multiplied the savings for each heating type by the number of units. The adjusted savings equaled the sum of the savings for the three heating types. The extrapolated savings increased almost 50%, from 0.22 to 0.31 Quads. The increase is principally due to the large fraction of central furnaces REM assumes will be constructed in new homes. This corresponds to an average space heating use of about 13,000 kWh/year. However, it appears that the shift to heat pumps is occurring faster than predicted by REM; in which case, the savings will be lower.

Floor area adjustment. Space heat demand clearly varies with the floor area. The first-order correction assumes that space heating varies linearly with floor area. We therefore introduced a floor-area adjustment.

REM does not explicitly give the average floor area of its electrically-heated home; however, The Characteristics of New Housing (1985) gives average floor area for all new houses built in 1985.

Table B-1. Floor areas for single family houses from *The Characteristics of New Housing (1985) and the Residential Standards Demonstration Program.*

Region	*Floor Area (sq.ft.)*
USA	*1785**
West	*1770**
RSDP	
Total	*1701†*
MCS	*1960†*
Control	*1560†*

* *Floor areas for all new houses (all heating types)*
† *Floor areas for electrically heated homes.*

Electrically heated houses are probably no different in floor area than houses with other fuel types. If this is true, the Control houses are smaller than the national average and the MCS are larger. We assumed that the original savings are for Control houses, so the savings need to be scaled up to reflect the smaller size of the Control houses. This increases the nationwide savings about 15%, from 0.32 to 0.37 Quads. The average house would use 9600 kWh/year.

Climate adjustment. REM also does not specify the location and climate for the new homes. According to the Characteristics of New Housing of, most of the electrically-heated homes are being built in milder climates. (Heat pumps in particular are much more common in the South.) Therefore a climate adjustment is warranted.

The Northwest climate spans 4000 - 10,000 degree-days, but we estimate that the weighted RSDP average is approximately 6000 degree-days. Meyers estimates that the average for all homes heated with electricity is about 3800. We scaled the savings by degree-days, which reduces the nationwide savings from 0.36 to 0.23 Quads. After the climate adjustment, the average house would use 9600 kWh/year. Energy savings — both absolute and percentage — do not scale directly with degree-days. This correction procedure is most error prone in mild climates (where the electrically heated homes are concentrated) and for homes with heat pumps. We suspect that larger savings could be obtained in milder climates because small improvements in thermal performance can dramatically reduce heating use. Note that these savings do not include the benefits of reduced cooling loads.

Thermal quality adjustment. Levels of insulation in homes is a key determinant of the extrapolated energy savings (and costs). The object would be to adjust the savings to reflect the difference in insulation levels between RSDP Control homes and national construction practices. It is possible to adjust for current insulation levels because RSDP has excellent data on insulation levels. Unfortunately, we did not have access to the latest NAHB nationwide data, so we did not perform this adjustment. However, we suspect that the Control houses had less insulation than the rest of the country (due to low electricity prices). An adjustment would probably decrease overall savings.

Inside temperature adjustment. Inside temperatures also determine space heating energy use. RSDP has both reported and measured inside temperatures. RECS collects reported thermostat settings in houses, but the data are in an awkward form. In the time available, we were not able to make the two sources comparable but, in principle, an adjustment is possible. We cannot predict the direction of the adjustment.

REM baseline adjustment. We also compared the energy use of the Control houses to that indicated for new houses in REM. The REM estimates for nationwide space heat were much, much higher than we found in the Northwest. It is not clear why the estimates are so high because most of the key determinants (discussed above) suggest that houses in the Northwest use more than average. Nevertheless, the difference could be due to higher thermostat settings, poorer insulation, or larger floor areas than found in the Northwest.[4] If we were to adjust the savings to reflect the difference between Northwest Control houses and the REM estimate, then the savings would increase 40%, from 0.23 to 0.32 Quads, and the average house would use about 13,000 kWh/year.

The order in which the adjustments were made was arbitrary. As a result, the peak absolute savings will vary. We present below the fractional changes resulting from each adjustment.

Costs of the Measures

The RSDP collected very detailed estimates of the incremental costs of the conservation measures. Vine estimates that the average incremental cost of the Model Conservation Standards was about $3 per square foot, or about $5700 for the average new MCS house (Vine 1986). This corresponds to about a 7% increase in the total house price. The measures included more insulation, triple-glazed windows, additional air leakage reduction measures, and heat exchangers. Based on the experience gained in the RSDP, lower cost packages could achieve greater energy savings. The principal problem was use of expensive heat exchangers -- typically 25% of total incremental cost -- to provide negligible improvements in air quality. At the same time, no attempts were made to improve heating system efficiency, even though such measures were clearly cost-effective.

The status of current construction practices in the rest of the country -- in particular the South -- is poorly documented. Extrapolations based on all new construction (i.e., including gas) is hazardous, because electrically heated homes have been traditionally better insulated. Still, the measures are not radical, so a simple (or raw) extrapolation will give at least a "ball-park" estimate of the nationwide cost. For the 7.7 million electrically-heated houses which REM assumes will be built in the next decade, achieving the .32 Quads/per year savings will cost $44 billion. This corresponds to a cost of conserved electricity of about 8¢/kWh.[5] At the same time, most of these measures will dramatically cut cooling

[4] If the BECA estimate is closer to reality, then it is worthwhile speculating how the misallocated energy is actually used. One possibility is that the extra electricity in the REM forecast may actually be used for miscellaneous purposes (or, the "other" end use). There are some indications that the miscellaneous uses of residential energy may be larger than once thought. (See "Saving the Other Energy in Homes", *Energy Auditor & Retrofitter*, Nov/Dec 1987.) No research has been undertaken to monitor the miscellaneous uses of energy.

[5] This is based on a capital recovery factor using crf(3%, 30 yr)= .05 ; however, the CCE jumps to 12¢/kWh using a crf(7%, 30yr) = .08

Table B-3. Summary of BECA-A adjustments.

Step 1: Estimate "raw" potential.

Approach: Multiply average RSDP savings by stock of electrically-heated homes that REM estimates will be built between 1988-1997.

$$Extrapolated\ savings = 2450\ kWh/year \times 7.7\ million\ houses$$

Results: After conversion to resource energy, extrapolated savings is about 0.22 Quads/year.

Refer to: Figure B-1 and Figure 3.

Step 2: Extrapolate savings by heating type.

Approach: Use disaggregated data from RSDP and REM for heating type. For the heat pump, the savings are,

$$stockwide\ heatpump\ savings = 1938\ kWh/year \times 3.318\ million\ houses$$

For the electric furnace, the savings are,

$$stockwide\ electric\ furnace\ savings = 5185\ kWh/year \times 3.436\ million\ houses$$

The savings for each heating type (heatpump, central furnace, and baseboard) are combined to yield the nationwide savings.

Results: After conversion to resource energy, extrapolated annual savings were 0.315 Quads.

Refer to: Figure B-2 and Figure 3.

Step 3: Adjust savings for floor area.

Approach: Recognize that national average of new home floor area is about 1.14 larger than RSDP houses. Assume that difference applies to all heating system types.

$$stockwide\ savings = 1.14 \times (savings\ from\ previous\ step)$$

Results: Stockwide savings are .36 Quads per year.

Refer to: Table B-1 and Figure 3.

Step 4: Adjust savings for climate differences.

Approach: Since RSDP houses are located in colder climates than most new electrically-heated homes, the RSDP savings must be lowered. We scaled the savings by degree-days, and assumed that the weighted RSDP average as 6000 degree-days and the stock 3800.

$$climate\ adjusted\ savings = \frac{3800}{6000} \times (savings\ from\ previous\ step)$$

No distinction is made for geographical concentrations of particular heating system types or that heat pump efficiency does not scale with degree-days.

Results: The climate adjustment lowers overall savings to 0.23 Quads per year. This corresponds to 7100 kWh per year for the average electrically-heated house built between 1988-1997.

Refer to: Figure 3.

Step 5: Scale savings for difference in pre-retrofit energy intensity.

Approach: Compare REM's UECs for new homes with RSDP value (after all adjustments). Scale the savings by this ratio.

Results: REM estimated the UEC for new, electrically heated houses (between 1988-97) to be 13000 kWh per year, while the adjusted RSDP was only 9600 kWh per year. Savings were benchmarked to REM by scaling the UECs.

$$\textit{Benchmarked savings} = \frac{13000}{9600} \times (\textit{savings from previous step})$$

Refer to: Figure 3.

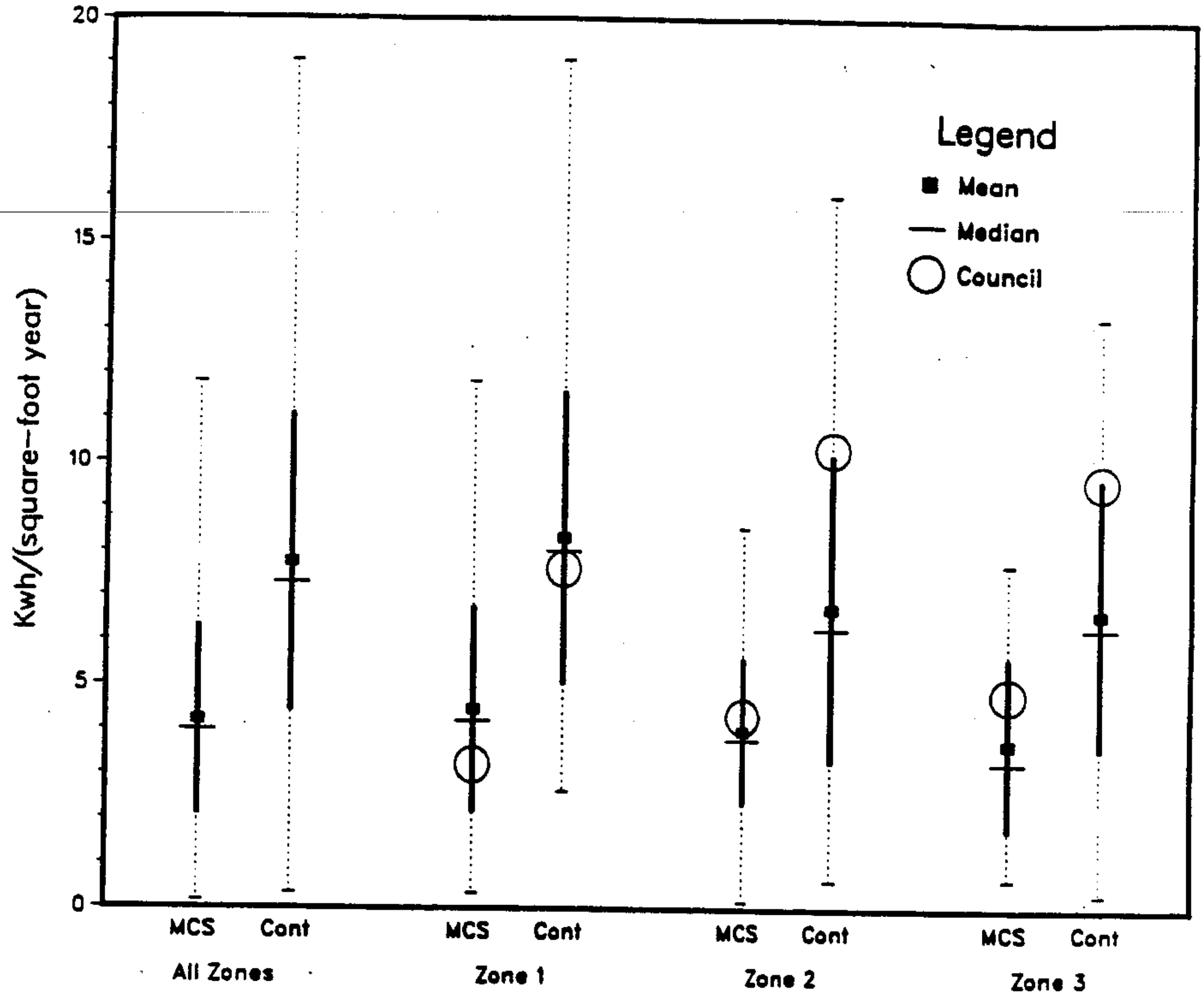

Figure B-1. Measured space heating use found in the Residential Standards Demonstration Program. The MCS houses were built to an energy efficient standard, while the Control houses were built to current practice. Zones 1 - 3 represent increasingly cold climate zones in the Pacific Northwest: Zone 1 is 4000 - 6000 degree-days, Zone 2 is 6000 - 8000 degree-days, and Zone 3 is 8000+ degree-days. "Council" values are simulations of prototype houses. For each group of houses, the chart shows the maximum value, minimum value, and the standard deviation from the mean (solid line).

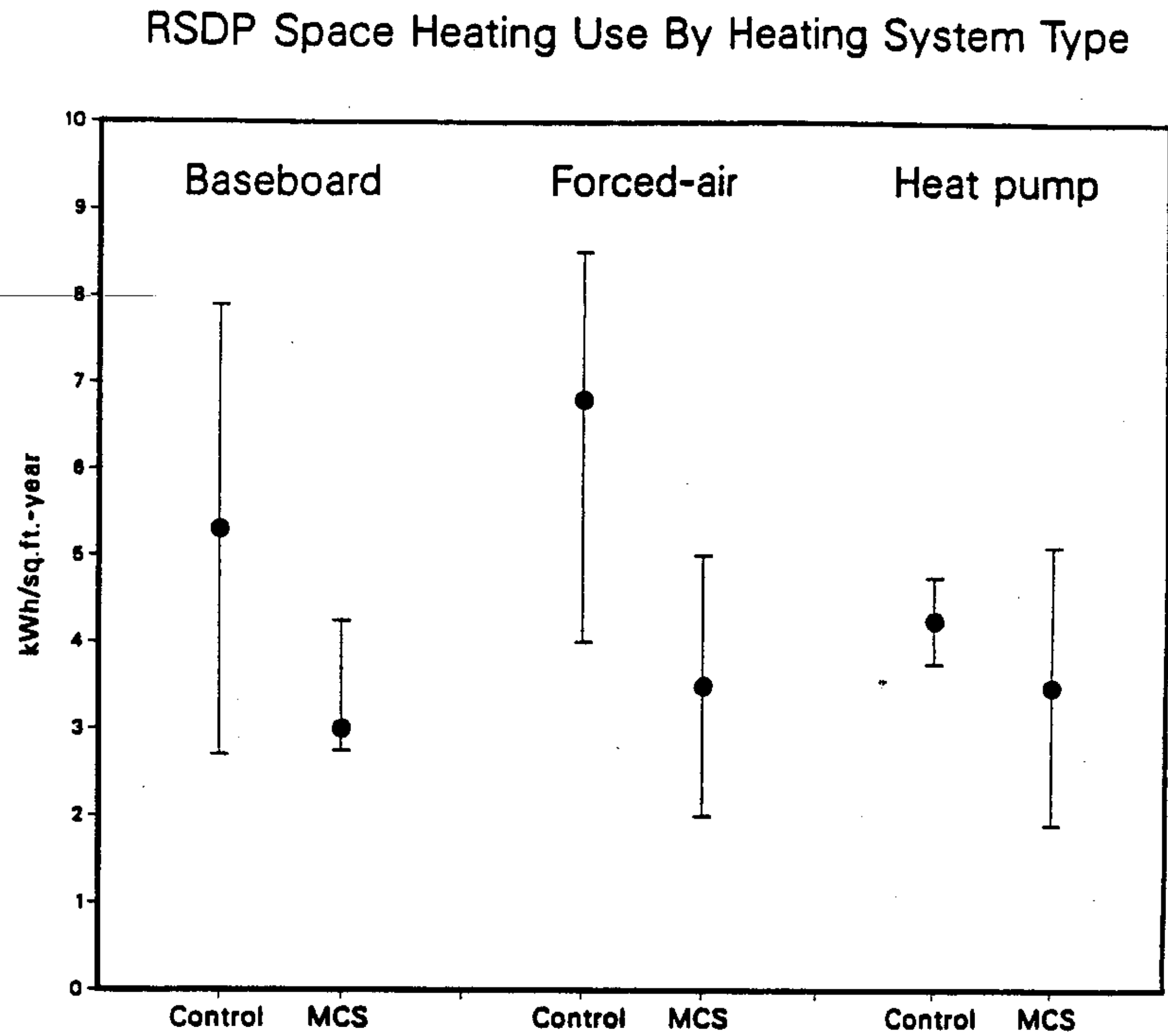

Figure B-2. Space heating energy use by heating type in the RSDP. (Adapted from Danny Parker ,"Performance Results from the Residential Standards Demonstration Program" Northwest Power Planning Council, Helena, Montana, August 1987.)