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DISCLAIMER

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MEASURED SAVINGS AND COST-EFFECTIVENESS OF CONSERVATION RETROFITS IN COMMERCIAL BUILDINGS *

Volume 1: Analysis and Results

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TABLE OF CONTENTS

VOLUME 1

LIST OF TABLES

LIST OF FIGURES

VOLUME 2*

*Volume 2, Technical Appendices, is available as a separate LBL Report, # LBL-28604.

Abstract

In this study, we examine the measured savings and cost-effectiveness of 447 commercial retrofit projects, representing over 1700 buildings. Topics include savings and cost-effectiveness by building type and retrofit strategy, savings from individual measures, peak electric demand savings, comparisons of measured vs. predicted savings, the persistence of savings in the years following a retrofit, and retrofit performance by year of installation. We also discuss lessons learned from submetering, the effect of weather normalization, impacts of growing office equipment usage, and the role of "energy management" in commercial buildings. Key findings are:

- Median annual site energy savings amounted to 20 kBtu/ft^2,[1] or 18% of whole-building usage; median retrofit cost was \$0.56/ft^2 (1988 \$), the median payback time was 3.1 years, and the median cost of conserved energy was \$3.10/site MBtu. The typical building owner was willing to invest in energy conservation an amount equal to only about 8 months of energy costs.
- Median pre-retrofit energy intensity, for all building types in the data base, was higher than that of the corresponding U.S. stock. Following retrofit, only offices and non-hospital health care buildings dipped below the stock median, and remained considerably above energy intensities typical of new, energy-efficient buildings. This fact, combined with evidence that a significant share of U.S. commercial buildings are still without even basic energy-efficiency measures, suggest considerable remaining potential for saving energy through energy management in the commercial sector.
- Changes to the HVAC system were the most popular retrofit strategy, installed in 85% to 95% of the projects in each building category (education, health, office, retail, and other). Lighting retrofits were done in over half of the offices and retail establishments, but in only one-third of the health care projects and one-sixth of the schools. Shell retrofits, most commonly roof insulation or window replacements, were installed in one-third of the schools but in only about one-fifth of the other building types.
- When examined by retrofit strategy, we found that projects with only HVAC and/or lighting retrofits had median payback times of one to three years, while those affecting the building shell, either alone or in combination with other types of measures, had payback times of five or more years.
- Projects in which *only* maintenance practices were changed typically saved 12% of their pre-retrofit consumption, often using in-house labor. Where maintenance costs were reported, payback times were very short; the median was about 1 year.
- Projects sponsored by the Institutional Conservation Program (ICP) included more shell measures (with long payback times) and relatively fewer HVAC and lighting retrofits than projects paid for by the building owner; the ICP projects were generally less cost-effective than the owner-paid retrofits in our data base.

[1] For the convenience of the majority of U.S. readers, we show energy data throughout this report in English rather than SI units. Those more familiar with SI units can refer to the following conversions: 10^3 Btu = 1 kBtu/ft^2 = 11.35 MJ/m^2, and 10^6 Btu = 1 MBtu = 1.055 GJ.

- For the buildings in this data set, retrofits installed after 1983 had lower savings, higher costs, and longer payback times than measures installed earlier.
- Very few predictions of savings (about one in six) came within 20% of measured results.
- Over half of our projects had multiple years of post-retrofit data; energy use continued to decrease for most of these buildings. However, for projects which reported fuel and electricity use separately, median electricity use increased in each of the years following the retrofit, probably due at least in part to increasing office equipment loads.

Our research suggests that, despite significant savings and short payback times for the majority of projects, savings often fall well short of economically optimum levels. This is due to limited owner willingness (or financial ability) to invest in all cost-effective measures, as well as to improper retrofit installation and/or maintenance. A comprehensive understanding is needed of energy management as a *process* rather than a one-time event, including both inspection and commissioning of installed retrofits and ongoing tracking of energy consumption as an indicator of operating problems.

INTRODUCTION

In 1986, there were an estimated 4.2 million commercial buildings in the U.S., accounting for 2.65 quads of fuel consumption and 700 TWh of electricity usage,[2] at an annual cost of $61 billion (EIA, 1989b). Fuel use in 1986 had declined about 9% from the values reported in 1983. However, electricity use was up 7%, despite extensive energy conservation retrofits and energy-efficient building codes in new construction. The increase in electricity use was due to growth in commercial floorspace; the tendency toward all-electric heating, ventilation, and air-conditioning (HVAC) systems in new commercial buildings; and increased energy intensities in some existing buildings from added office equipment and other miscellaneous equipment loads.

Despite projected growth in commercial sector floorspace of 2.5 percent per year, about two-thirds of the commercial floorspace anticipated for the year 2000 is already in place, and is thus a prime target for energy efficiency improvements (DOE, 1981). The technical potential for energy savings in the commercial sector has been estimated at about 40-50% (MacDonald, 1986 and MacDonald, et al., 1986).

Most estimates of energy savings resulting from conservation retrofits in commercial buildings are based on engineering calculations, computer simulations, or "professional judgment." A compilation of *measured* data on commercial retrofit savings and cost-effectiveness is important as an empirical benchmark for these estimates. Measured data also provide a source of improved credibility, feedback on the accuracy of savings predictions, and a means of identifying new issues that deserve more concentrated data collection and analysis. Better retrofit performance data has been identified as a key research need by the Department of Energy, in its multi-year research plan for existing buildings (MacDonald, et al., 1988).

The "Buildings Energy Use Compilation and Analysis" (BECA) project at Lawrence Berkeley Laboratory addresses these needs by compiling and analyzing *measured* data on the energy performance and economics of residential and commercial buildings designed or retrofitted with energy saving features.[3] Each BECA compilation is periodically updated.

The initial data on retrofitted commercial buildings (BECA-CR) were published in 1983 and updated in 1984; the latest update included 311 retrofitted commercial buildings (Ross and Whalen, 1983; Wall and Flaherty, 1984; Gardiner, et al., 1984). At that time, measured data on conservation retrofits were almost always in the form of utility billing data, and typically reflected the savings from a package of retrofits, rather than individual measures. Although many retrofits continue to be evaluated on the basis of change in utility bills, an increasing number of commercial buildings retrofits are submetered, either on a short-term basis or for an extended period. These more detailed data make it easier to isolate energy and peak demand savings for individual retrofit measures. In the previous BECA-CR report, energy consumption was not normalized (other than for floor area), as little research had been done on appropriate

[2] 1 quad = 10^{15} Btu; 1 TWh = 10^{9} kWh.

[3] Sectors addressed by BECA databases include: new, low-energy homes (BECA-A); retrofits of existing residential 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 (415-486-7288).

adjustment techniques for weather and operating conditions in commercial buildings. In this analysis, we examine the effects of simple weather normalizations for a subset of buildings. Effects of retrofits on peak load, or electricity by time-of-use, were not investigated, in the absence of data.[4] In recent years, load management has become a driving force behind many commercial building retrofit investments, due to electric utility rate structures which increasingly emphasize peak demand charges. Retrofits such as thermal energy storage systems may be highly cost-effective to the customer and the utility by reducing on-peak electricity demand and shifting energy use to off-peak periods, even without a reduction in total energy use (Piette and Wyatt, 1988; Meal, et al., 1985).[5]

In addition to expanding the earlier data set by 50%, this update of the BECA-CR compilation addresses the issues of individual retrofit savings, weather and occupancy normalization in selected cases, electric peak demand savings, and the impact of office equipment load growth on retrofit savings. Other issues addressed in this report include predicted vs. actual savings, persistence of savings, and refinements in cost-effectiveness indicators. The next sections summarize our data sources, analysis methods, and then present results and their implications for energy policies, retrofit investment decisions, and future research.

DATA SOURCES

The 447 projects contained in the BECA commercial retrofit database represent 1779 U.S., Canadian, and European commercial buildings (see Appendix A for summary data tables and Appendix B for descriptions of each retrofit project).[6] Because the BECA database is drawn from available, well-documented measured performance data, rather than a statistically chosen sample, it is not representative of the existing stock or of the retrofitted stock of buildings in this country. In the section on "Building Characteristics and Stock Comparison," we discuss how the characteristics of the projects in BECA compare to the U.S. stock.

About one-third of the projects were added to the compilation during this update. Not all of these additions represent recent retrofits: over half of the newly-entered data are for retrofit projects prior to 1984 (the date of the last BECA commercial retrofit compilation). These projects were not included in earlier BECA studies, because the data had not been released in time.

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[4] The Energy Information Administration's Nonresidential Buildings Energy Consumption Survey (NBECS) did not report demand data prior to 1986. Demand data were included in the 1986 NBECS survey, partly in response to LBL's request for a nationally representative benchmark with which to compare buildings employing demand-leveling measures (Burns, 1988).

[5] In many cases, total electricity use increases due to additional pumping requirements and thermal losses from storage tanks.

[6] Throughout this report, we use the term "project" to refer to a retrofitted building or group of buildings which are entered as one data point in the BECA database. For a few projects, a series of retrofits were installed several years apart, which enabled us to analyze savings separately for each retrofit. We use the term "retrofit packages" to refer to these separately analyzed groups of retrofits; the total number of retrofit packages examined is 455. In some of the figures and tables which follow, the number of projects differs from 447 or 455, depending on the availability of data for a specific analysis. For example, projects without cost data or whole-building consumption were omitted from those analyses.

A variety of means were used to identify and solicit retrofit data, including literature review, publication of a "case study request" in a number of trade journals and newsletters, and review of data from the Institutional Conservation Program (described below). The majority of data came from utilities, research institutions, and state and local energy offices, primarily because these organizations had sufficient time and interest to compile the necessary information. Although energy service companies are responsible for a growing share of the retrofit activity in the commercial stock today, they were often reluctant to contribute data to BECA, due to time constraints, the proprietary nature of their savings and cost data, and a concern over disclosing the methods used to adjust billing data when estimating retrofit savings.

METHODOLOGY

For each retrofit project, we collected a brief description of the building(s), retrofit measures installed, retrofit costs (if available) and date, and metered pre- and post-retrofit energy consumption data. We also sought more detailed information on HVAC systems, lighting and process loads, and operating schedules. Each record was assigned a confidence level for three data categories: building characteristics, retrofit data, and energy data. Confidence levels for specific projects are listed in Appendix A, along with the rating criteria. Only 16 projects are rated "A" or "A+" in all three categories, indicating high-quality building characteristics data, information on retrofit measures, installed costs, installation dates, and submetered or monthly whole-building energy use and cost data, for at least one year pre- and post-retrofit. One-third of the projects in the data base are rated "B" or higher in all categories. This generally means either that retrofit costs were not available, or that only annual energy consumption was reported. However, the quality of available data is improving compared to our earlier compilation; one-half of all the records entered during this update were rated at least "B" in all categories.

Energy Intensity and Savings

The quality of energy data varied widely: for one-third of the projects only annual energy use data were available; the other two-thirds had monthly utility bills for at least one year before and after the retrofit was installed. Only 14 of the projects had submetered data, either for short periods (a few weeks to a few months) or for one year or more. Annual peak demand was reported for 12% of the projects. Twenty projects had submetered energy consumption, sufficient to evaluate the retrofit savings but (in the absence of long-term and/or whole-building energy use data) not appropriate for comparisons with other buildings. These projects were excluded from summary values on whole-building energy intensity and percent savings, as cited in the remainder of this report.

Energy use intensity (annual kBtu/ft^2) is calculated separately for both electricity and fuel, and then summed in terms of site energy (at 3413 Btu/kWh for electricity) and resource energy (at 11,500 Btu/kWh). For projects with more than one year of pre- or post-retrofit consumption, each year of data is entered in the data base, but the *average* pre- and post-retrofit consumption is used to calculate savings. This "pre/post" analysis allows a straightforward comparison of energy savings with retrofit investments. However, it does not reveal how close the building is to reaching its energy efficiency potential. Therefore, we also compare post-retrofit energy intensity to average energy intensities for similar buildings in the U.S. stock, and with new, energy-efficient commercial buildings. Only "raw" (unadjusted) energy use data were entered in BECA, even though many of the data sources also included weather- or occupancy-normalized results. (See the section on "Effects of Weather Normalization"for a comparison of raw and weather-corrected savings.) Entries for some projects represent aggregated results for more than one building; this was most often the case for retrofits financed under the Institutional Conservation Program, due to the sheer number of buildings included in this program and the difficulty of obtaining well-documented, building-by-building data.

Submetered Buildings

For the 8 projects which had all end-uses submetered, consumption for individual end-uses was entered in a separate database (see Appendix A), but only the change in whole-building consumption was used to evaluate savings. In some cases, one or more end-uses were submetered, but not the whole building. Appendix B contains a discussion of the effects of retrofits, by end-use in individual buildings. Percentage energy savings discussed later in this report exclude these cases; the percentage savings are all based on whole-building usage.

In a few cases, lighting retrofits were submetered for only a short period (ranging from a few weeks to a few months) before and after installation. Energy use for these projects was scaled up to annual values based on the number of working days.[7]

Retrofit Costs and Economic Indicators

Retrofit costs were reported for over two-thirds of the projects in this study; these data reflect the contractor-installed cost of each measure. Earlier BECA compilations included many projects where cost data were missing. For this update, we included projects without cost data only if some other aspect of the project was very interesting (e.g., an innovative retrofit strategy, or submetered energy data). For U.S. buildings, we adjusted actual retrofit costs and energy prices to 1988 dollars, using the GNP deflator. For projects in other countries, original energy and retrofit costs were translated to 1981 local currency using that country's GDP cost deflator, converted to U.S. dollars using 1981 exchange rates, and then expressed as constant 1988 U.S. dollars using the U.S. deflator.[8]

In addition to comparing retrofit costs for different types of buildings and measures, we also calculate a "conservation investment index," which is defined as the ratio of retrofit cost to pre-retrofit annual energy expenses. This can be interpreted as "the number of years of energy costs" invested in a retrofit project. Comparisons using this index can reflect the effect of local energy prices on conservation investment decisions.

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[7] We used working days, rather than total days, as the former gives a more conservative estimate—and probably more valid—estimate of absolute energy savings.

[8] We considered exchange rates for 1981 fairly typical of long-term trends; using this as a reference year reduces the effect of fluctuating exchange rates in more recent years.

Four economic indicators were calculated to characterize the cost-effectiveness of retrofit investments:

- simple payback time based on national average energy prices,
- simple payback time based on project-specific energy prices,
- the cost of conserved site energy, and
- the cost of conserved resource energy.
  (Ruegg, 1980; Meier, 1983).

The simple payback time (SPT) is defined as:

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

where:

$FC =$	first cost of retrofit
$\Delta E =$	annual energy savings
$P =$	energy price (national average or local price during the year after retrofit)
$\Delta OMC =$	increase in annual operations and maintenance costs.[10]

Simple payback time is a commonly-used indicator of retrofit cost-effectiveness; it is familiar and easily understood by most commercial building owners and managers. Where lifetimes are long or interest (discount) rates high, a discounted payback period may be preferred. One disadvantage of the payback period as an indicator is that it does not reflect differences in useful lifetimes beyond the payback date—which is very short for most commercial retrofits in the data base.

Use of national average energy prices may provide the most valid comparison among buildings in different regions of the country. However, paybacks calculated using project-specific ("local") energy prices often reflect more accurately the investment perspective of each building owner. We were able to calculate paybacks based on local energy prices for one-fourth of the projects. Because information on electricity rate structures was available for only a few projects, the electricity prices reflect *average* rates (total billed cost divided by total kWh consumption). In other words, the impact on payback time of changes in electricity peak demand was **not** taken into account (nor were other load-shape changes associated with some retrofits, such as a shift of energy use to off-peak periods). For payback times based on national-average energy prices, we used 1988 U.S. average fuel and electricity prices for the commercial sector ($4.23/MBtu and $0.07/kWh; EIA, 1989a). Because local energy prices were not available for most of our records, we show payback times based on national-average energy prices in the tables and figures in this report. Paybacks based on local prices are listed in Appendix A.

[10] Changes in maintenance costs were reported for 24 projects; most of these were energy management systems. In all but two cases, maintenance costs increased as a result of the retrofit. The average annual change in maintenance costs amounted to 6% of the initial retrofit cost.

We also calculate the cost of conserved energy (CCE), which can be used to compare conservation investments to purchases of fuel or electricity (in either site energy or resource energy terms). The CCE takes into account differences in expected retrofit lifetimes, which the payback time does not. CCE is found by dividing the annualized cost of the retrofit by the annual (site or resource) energy savings. It can be expressed as:

$$CCE = \frac{FC * CRF + \Delta OMC}{\Delta E} \quad (2)$$

where:

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

d = discount rate

n = lifetime of measures

Conservation investments are amortized over the measures' expected physical lifetimes, using a real (i.e., constant-dollar) discount rate of seven percent. The CCEs we report are in constant 1988 dollars. Since estimates of retrofit lifetime can vary widely, we used results from a survey of retrofit lifetimes (McRae, et al., 1988) rather than the estimated lifetimes reported by individual organizations contributing data. Although expected lifetimes of retrofits are difficult to define, we believe that the use of a consistent source of retrofit lifetimes allows a fairer comparison of retrofit cost-effectiveness.

BUILDING CHARACTERISTICS AND STOCK COMPARISON

Structural Characteristics

This study examines the results of 447 non-residential retrofit projects, ranging from prisons and post offices to warehouses and hotels (but excluding manufacturing and other industrial buildings). Table 1 compares the characteristics of projects in this study with those of the U.S. stock, both in terms of the percent of projects and the percent of floor area.[11] Ideally, we would like to compare BECA characteristics with those of the *retrofitted* stock, but such stock data, while collected as part of NBECS, are not currently available. Although BECA buildings are not deliberately chosen to represent the U.S. commercial stock, they are quite diverse in terms of type, size, location, and vintage.

As shown in Table 1, there is at least some BECA coverage for most major categories of commercial buildings.[12] The BECA database over-represents educational and health-care buildings, and under-represents assembly, food sales/service, and warehouse buildings, both in terms of the fraction of projects and of floor area. Although it appears that the proportion of offices

[11] Characteristics of the U.S. commercial building stock are taken from the Nonresidential Buildings Energy Consumption Survey (NBECS) (EIA, 1988 and 1989b).

[12] Building types are taken from NBECS. "Other" assembly buildings include libraries, museums, and recreation centers; "other" health care buildings are medical clinics, development centers, and psychiatric centers; "small" offices are ≤ 50,000 ft^2 and "large" offices are > 50,000 ft^2.

and retail stores is about the same as in the stock, the BECA retail sample consists almost entirely of post offices.[13] Very large buildings (over 100,000 ft^2) are over-represented in the BECA data base, compared with the U.S. stock, while very small ones (under 10,000 ft^2) are under-represented. Larger buildings are also over-represented within specific building-type categories. The over-representation of large buildings can be attributed to two factors: retrofits are more likely to be installed in larger buildings,[14] and large-scale buildings are more likely to have a professional energy manager or other individual responsible for tracking energy performance and recording data suitable for BECA. By region, more BECA projects are located in the northeastern U.S., and fewer in the South, than is true of the stock. The projects in this study tend to be older than the stock; almost none of the BECA buildings were constructed after 1980, compared to 15% of the buildings in the stock.

Pre-Retrofit Energy Intensity

Before retrofit, almost all buildings in the data set were more energy-intensive than the median for the corresponding building type in the U.S. commercial stock (Figure 1). Some of the discrepancy may be caused by differences in the projects' location: commercial buildings in the Northeast (heavily represented in BECA) are typically more energy intensive than those in the South (under-represented in BECA). In addition, a lower percentage of BECA projects are all-electric than is true of the stock (12% vs. 23%). This may tend to make the energy intensities of BECA projects, expressed as site energy, relatively higher, since combustion equipment losses are counted at the building level rather than at the power plant. Pre-retrofit energy costs were reported for one-third of the BECA projects; the median cost per square foot (not shown in Table 1) was about the same as for the stock ($\$1.05/ft^2$ vs. $\$1.07/ft^2$, in 1988 \$).

RETROFIT MEASURES AND COSTS

Figures 2 and 3 illustrate the retrofit measures implemented in different types of buildings. In Figure 2, retrofits are grouped into the general categories of HVAC, shell, and lighting measures. Comparisons are shown for the fraction of retrofits in the corresponding portion of the U.S. commercial building stock. Figure 3 shows the specific retrofit measures installed in all the buildings we examined (not subdivided by building type). In both figures, the number of retrofits is greater than the number of projects, since more than one measure is typically installed in a building. (See Appendix A for descriptions of each retrofit type.) HVAC system retrofits were by far the most popular conservation measures in all types of commercial buildings. Frequently implemented HVAC retrofits include improved maintenance, retrofits to the ventilation system, and HVAC controls such as energy management systems or time clocks. Some type of

[13] Post office buildings would typically be classified as "retail," which is the convention we followed here. However, note that the retrofitted facilities included in the data base were large postal service centers. Almost all had floor areas well in excess of 100,000 square feet and extended operating hours (24 hours/day in many cases), but with space conditioning requirements probably lower, in most cases, than a comparably sized retail building. From an energy perspective, comparing these postal facilities with other light-industrial or warehouse facilities might be equally appropriate.

[14] Only 5% of commercial buildings with less than 50,000 ft^2 have been retrofitted (following an energy audit), compared to 17% of those with greater than 50,000 ft^2 (EIA, 1988).

HVAC retrofit was done in 85% to 95% of the projects in each building category (education, health, office, retail, and other). Lighting retrofits were done in only 16% of the schools and 31% of the health care projects, but were installed in over half of the offices and retail projects. Changing the type of lighting system (e.g., from incandescent to fluorescent) was the most common lighting retrofit, while changes in lighting levels (delamping) and installation of lighting controls (e.g., occupancy or daylight sensors) were also popular lighting measures. Shell retrofits, most commonly roof insulation or window replacements, were installed in one-third of the schools but in only about one-fifth of the other building types.

Figure 2 also compares retrofit activity in the BECA buildings with post-audit retrofits[15] of the U.S. stock (EIA, 1988). For all building types, more HVAC retrofits were implemented in BECA projects than in the stock. For education and health buildings, fewer lighting measures were carried out in BECA projects, compared to the stock, while the fraction of shell measures was about the same. In offices and retail stores, the reverse was true: shell measures were much less common in the BECA projects than in the stock, while lighting retrofits were implemented about as often.

Costs were reported for 70% of the retrofit packages in this study. The median retrofit cost was \$0.56/ft^2, with one-quarter of the retrofits costing less than \$0.25/ft^2. If examined by building type (see Table 2), retail buildings (mostly post offices) had the least expensive retrofits with a median of \$0.36/ft^2, while hospitals typically had the most costly measures (\$1.10/ft^2). For the 140 projects which reported local energy costs, the median investment intensity was 0.7 years (of energy costs).

ENERGY SAVINGS AND COST-EFFECTIVENESS

Median annual site energy savings were 20 kBtu/ft^2 (1 kBtu=10^3 Btu), or about 18% of whole-building energy use prior to retrofit. Table 2 summarizes key indicators of energy savings and cost-effectiveness, by type of building and project sponsor. For all retrofitted buildings (both mixed fuel and electricity and all-electric), median fuel savings were 12 kBtu/ft^2 and median electricity savings were 0.66 kWh/ft^2. For the 54 projects in all-electric buildings, median electricity savings were 22% (4.59 kWh/ft^2). In about 10% of the retrofit projects we examined, energy intensity *increased* following the retrofit. Over 60% of these projects with "negative savings" were schools; in one-third of these cases, changes were made in maintenance practices only. The energy savings from improved maintenance may have been too small, compared with other factors related to pre-/post-retrofit differences in weather, occupancy, or added loads. Or, the new maintenance practices may not have been adequately followed throughout the post-retrofit period.[16]

When examined by building type (Table 2), health care buildings had the highest absolute savings per square foot of floor area, and educational buildings the lowest. In percentage terms,

[15] The stock retrofits actually represent conservation measures added *after audits*; *total* retrofit activity is not included in published NBECS reports at this time. Therefore, the number and percent of stock retrofits is underrepresented here.

[16] If we remove the 45 retrofit packages which did not save energy from the total statistics, median energy savings rise to 23 kBtu/ft^2, or 20% of whole-building usage.

however, savings in offices and retail stores were the highest. For schools and health care buildings, median electricity use stayed the same or increased following retrofit, while electricity savings in offices and retail stores were a significant component of total savings. Figure 4 shows energy savings as a function of pre-retrofit energy intensity; half of the retrofit packages saved between 10 and 30% of pre-retrofit use. For a given level of pre-retrofit energy intensity, savings vary considerably, even for buildings of the same type.

Following retrofit, Figure 1 shows that median energy intensity is still higher than that of the corresponding part of the U.S. stock, for all building types except offices and non-hospital health care buildings. Post-retrofit energy intensity for hospital, college, and assembly buildings is still significantly higher than intensity for the stock, while energy use in elementary and secondary schools and in retail stores was closer to the stock averages. For all building types, post-retrofit consumption of the BECA-CR projects is still considerably higher than that of new commercial buildings designed to be energy-efficient, as reported in another BECA compilation (Piette and Riley, 1986). While it may not be cost-effective, in retrofitting and existing building, to implement all measures that are feasible in new construction, these indicators still suggest a substantial remaining potential for retrofits and ongoing energy management in existing U.S. commercial buildings, as discussed below.

The median simple payback time for the BECA sample is 3.1 years, as shown in Table 2. This value is calculated using 1988 national average energy prices. (The median is 2.6 years if only those projects with positive savings are taken into account.) This represents a significant increase over typical payback times from the previous BECA compilation of commercial retrofit data, with median paybacks of about 1 year. A number of factors may have contributed to longer payback times, including a larger number of shell retrofits and more publicly-funded measures in projects recently added to the database.

For the retrofitted buildings the median cost of conserved energy is $3.10/site MBtu, or $2.30/resource MBtu (1988 $). Retrofits in retail buildings (primarily post offices) were more cost-effective than those in other building types. Office conservation measures were the next most cost-effective, except when measured using the cost of conserved energy per site MBtu. In part, this is because offices had the highest fraction of all-electric buildings (40%). In addition, a relatively large number of short-lived measures, like some lighting and HVAC retrofits, were installed in offices. Education, health, and "other" buildings had longer median payback times (5 to 7 years) and higher costs of conserved resource energy, as shown in Table 2.

Savings by Retrofit Strategy

Figure 5 summarizes energy savings and cost-effectiveness results grouped by retrofit strategy. Each retrofit project was assigned to the narrowest category which encompasses all conservation measures in that building. For example, a building in which high-efficiency fluorescent lights were installed would be assigned to the "Lights" category, but one where the retrofit included both high-efficiency lights and variable-speed fan drives would be placed in the "HVAC & Lights" group. We found that projects with HVAC and/or lighting retrofits had median payback times of one to three years, while those affecting the building shell (changes to windows or insulation levels), either alone or in combination with other types of measures, typically had greater investments as well as longer paybacks: five years or more.

Changes in maintenance practices alone typically saved 12% of pre-retrofit consumption. Since it was common to use in-house labor for these projects, the costs associated with the maintenance changes were often not reported; where these costs were reported, they averaged about 20¢/ft^2, leading to very short payback times (median = 1 year). Almost all of the projects involving maintenance changes were in fuel-heated buildings; four-fifths of the maintenance projects were in schools, with the remainder in offices and health care buildings.

Savings from Individual Measures

Although most of the projects we studied involved several retrofit measures implemented at the same time, there were 33 projects in which single retrofits were installed, allowing us to isolate their effects. Savings and cost-effectiveness of these individual measures are presented in Table 3. Lighting controls, such as occupancy sensors, scheduling, or localized switching controls, were added to eight buildings, including five post offices and three office buildings. Average savings from the controls was 19% of whole-building usage (and thus a much larger fraction of lighting energy only); average payback times were about four years. Window modifications, including replacements, were installed in five groups of schools through the Minnesota, Utah, and Wisconsin Institutional Conservation (ICP) programs. Savings averaged 6% of pre-retrofit usage; the cost was typical of that for other shell retrofits. HVAC system controls were a very popular retrofit, installed in 35% of the projects we examined. Table 3 shows results for 20 projects involving only controls changes. We separated controls into two groups: (1) local HVAC controls, such as clock thermostats, boiler controls, and air conditioner controls, and (2) more comprehensive "energy management system" (EMS) retrofits, utilizing computerized control strategies. Both types of control systems were installed in a wide variety of building types, including schools, offices, post offices, hotels, and medical centers, though EMS were predominately used in large offices. All but one of the EMS were installed in buildings over 75,000 ft^2, whereas the local HVAC controls were more often used in smaller buildings. As shown in Table 3, the EMS resulted in higher savings, with costs per square foot of floor area slightly higher than those of local HVAC controls. However, the median payback time for the EMS retrofits was still over 10 years. The fact that many EMS systems perform functions other than energy management (fire safety, security, etc.) may help explain the willingness to invest in measures with such long energy paybacks.

The Role of Submetered Data in Understanding Savings

In most cases, it is not possible to isolate savings from individual measures installed, one at a time, in a building. Submetered end-use energy data are now beginning to be used to quantify retrofit performance. Eight buildings in our data base had submetered data on all end-uses, and lighting use only was submetered in an additional five projects. In each case, the submetered consumption data provided valuable insights to retrofit measure performance. For example, Seattle City Light and United Industries Corp. monitored seven buildings for one year before and one year after retrofit (Cleary and Schuldt, 1989). Some measures saved less energy than predicted, for a variety of reasons. Pre-retrofit conditions sometimes differed from those that were modeled: in one case, lighting controls saved less than expected because the store manager had manually controlled lights before the retrofit. In another case, existing lighting capacity had been overestimated. In one office building, dramatic changes in occupancy levels (from 40% to 75%) would have made it difficult to see the effects of the retrofit measure at a whole building level. In other buildings, the retrofits produced unexpected results (e.g., strong interactions between HVAC, refrigeration, and lighting retrofits and new thermostats which caused more frequent cycling of the HVAC system). Without submetered data to help identify these other influences on whole-building energy use, one could only guess at reasons why the expected savings were not achieved. The Seattle City Light study concluded that the simulation tool (DOE-2) had modeled the buildings well, given the input data; discrepancies between predicted and actual savings were mainly caused by misspecification of physical characteristics and/or operating schedules. The areas where the computer model did have problems were in simulating refrigeration and HVAC interactions, and modeling HVAC control strategies.

In another study, a large, all-electric office building was submetered from 1982 through 1988 (Larkam 1988). In early 1988, 40-Watt fluorescent lamps were replaced with 34-Watt lamps; following this retrofit, whole-building electricity use decreased by 3%. However, an examination of the submetered data showed that the change in consumption was mainly due to decreased HVAC usage. Lighting usage dropped by less than expected (4%), while energy used through receptacles increased by 6%. The end-use data led the project engineer to investigate lighting usage more thoroughly. He found that two factors—neither of them related to technology performance—had contributed to lower-than-expected lighting savings: some burnt-out lamps had been replaced during the retrofit, and the company switched to flex-time after the retrofit, resulting in longer operating hours. Another lighting retrofit study also found that replacement of burnt-out lamps accounted for the difference between actual and expected savings from replacing 40-W with 34-W lamps (Gettings and MacDonald, 1989).

These examples show how submetered data can help in understanding retrofit effects more thoroughly. End-use monitoring can also aid in evaluating retrofit performance more quickly. Six lighting retrofits were submetered for short periods (one week to several months) before and after retrofit. The shorter evaluation periods allowed researchers to test several alternative retrofit strategies and pick the one most suited to the particular building. For example, Lawrence Berkeley Lab researchers installed a programmable lighting control system in two large office buildings and tested the effect of "loose" and "tight" schedules on energy savings, demand reduction, and occupant satisfaction (as measured by how often schedule overrides were necessary) (Rubinstein and Karayel, 1984). The short-term monitoring allowed them to determine the schedule with the optimum combination of these factors. However, no work has been done to compare short-term and long-term monitoring results, and what causes discrepancies between the two. Such research would help target submetering for the buildings and retrofit types most in need of further analysis.

Demand Savings

Fifteen of the projects we examined were retrofitted with measures designed for load management. Energy management systems (EMS), either newly installed or enhancements of existing systems, provided control for the majority of these load management measures. In addition, one building was retrofitted with a specially designed "demand management system" being tested by a utility, and five post offices received "demand-limiting devices" of an unspecified type. Unfortunately, only four of these 15 buildings reported peak demand. Three of these buildings (two offices and a nursing home) reported peak demand savings of 21 to 27% (1.4 to 4.9 W/ft^2) following installation of EMS or demand management systems. The fourth building, in which an upgrade of the existing EMS was carried out, experienced slightly *increased* peak demand.

An additional 48 retrofit projects (mostly offices and some schools) reported peak demand, although the conservation measures were not specifically designed to affect demand. Three retrofit packages (HVAC system, lighting, and system and lighting combinations) were well-represented among the projects reporting changes in peak demand: HVAC system retrofits (20 projects) typically reduced peak demand by 0.15 W/ft^2, or 4%, lighting retrofits (9 projects) had a median demand savings of 0.06 W/ft^2,[17] and HVAC and lighting combinations (9 projects) typically saved 1.33 W/ft^2, or 22% of pre-retrofit peak demand. Six projects with energy management systems reported an average peak demand savings of 0.26 W/ft^2, or 7%. There was no marked difference in peak demand savings by building type. As noted earlier, the lack of data on electricity demand charges or savings precluded our including this component when calculating paybacks and other cost-effectiveness indicators.

Project Sponsorship: Owner-Paid, Institutional Conservation, and Other Grant and Demonstration Programs

To examine how retrofit cost-effectiveness varied by project sponsor, we divided the BECA-CR data set into three groups: owner-paid retrofits (62%), those funded through ICP (23%),[18] and those funded through other grant or as demonstration programs, typically utility grants or research projects (15%). Then, the types of retrofit measures and median savings and cost-effectiveness were examined for each group. Figure 2 shows retrofit measures by type of sponsor, while Table 2 summarizes savings and cost-effectiveness by sponsor type. With two exceptions, there was little variation, by type of sponsor, in the relative percentages of each major type of retrofit. One exception was that owner-paid retrofits were much less likely to include shell measures. A second exception was the tendency to include lighting measures in only 25% of the ICP retrofits, compared with 40-50% of the owner-paid and "other-sponsor" projects.[19] (The totals in Figure 2 add to more than 100% because multiple measures are often installed in one building).

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[17] This seems low, in view of the large contribution of lighting to peak load in most commercial buildings. However, an examination of the individual cases in Appendices A and B (LTA001,002, 004', 004", ORL001, SER001, SCL005, PIT001) shows percentage savings of peak load ranging widely, from over 50% (of lighting use only) in one case, due to extensive delamping and replacement with efficient lamps, reflectors and ballasts, to a second case where the (whole-building) peak load increased by 22%—but the retrofit involved night lighting. In cases where lighting retrofits involved relamping with efficient (34-W) lamps, or ballast replacements, peak savings were about 0.1 to 0.5 W/ft^2.

[18] One-quarter of the retrofit packages we examined were installed with funding from the Institutional Conservation Program (ICP), a $1.4 billion, multiyear program sponsored by the U.S. Department of Energy (Carroll, et al., 1988). Since its inception in 1979, conservation measures in over 20,000 schools and hospitals have been subsidized through ICP. We obtained information on the statewide programs in Minnesota, Utah, and Wisconsin, and on individual buildings in California, Illinois, and Ohio (see Appendix B for further descriptions of specific programs).

[19] One explanation may be that schoolrooms, unlike many office, retail, and other nonresidential buildings, are often built with modest levels of fluorescent lighting, so there are fewer opportunities for savings. Another possibility, in the case of hospitals and other institutional buildings, is that lighting measures are easier for the owner to pay for incrementally and install with in-house personnel; ICP grants would then tend to be requested most often for major equipment, control, or envelope measures requiring large up-front outlays.

As shown in Table 2, owner-paid retrofits and conservation measures funded through ICP had median costs of about \$0.45 and \$0.56/ft^2, respectively; retrofits paid for through other sources, mainly utility or government demonstrations or grants, typically cost twice as much. Retrofits funded by ICP had the lowest median savings, in absolute and percentage terms, of the three groups examined. The projects financed by other grants and demonstrations had the highest median savings, as would be expected given their higher levels of retrofit investment. Both the ICP retrofits and the other grant and demonstration projects had payback times two to four times longer than measures paid for by the building owner.

These differences in cost-effectiveness narrowed when examined in terms of the cost of conserved energy (CCE): although the retrofits sponsored through ICP and other grant and demonstration programs remained less cost-effective than owner-paid measures, the gap was significantly narrower. This discrepancy between cost-effectiveness comparisons using payback time and using CCE is associated with the greater tendency to install longer-lived envelope retrofits under ICP and other grant and demonstration projects. However, for all groups except the demonstration projects, the median CCE is less than national average 1988 fuel price of \$4.23/MBtu.

Savings and Cost-Effectiveness by Year of Retrofit

The projects in our study were retrofitted between 1974 and 1988. We examined time-trends in energy intensity, savings, and retrofit cost-effectiveness. We found that pre-retrofit energy intensity had declined slightly over this period, as might be expected with continued introduction of new technology and the spreading awareness of energy as a controllable component of operating costs. Both absolute and percentage energy savings have also dropped over this period, probably due to the shift in attention from relatively easy and obvious conservation measures ("cream-skimming") to more difficult and costly ones. For example, median savings for pre-1980 retrofits were about 20%, compared with 15% for post-1983 projects. Similarly, there was a tendency for retrofit costs (in constant 1988 \$) to increase over time, from a median of \$.50/sq.ft. prior to 1983 to \$.97/sq.ft. after 1983. Lower savings and higher retrofit costs imply significantly longer payback times for the more recent retrofits. Table 4 shows the trend in median payback times by type of project sponsor. For owner-paid retrofits, the ICP program, and other grant projects, median payback times have at least doubled between the pre-1983 and post-1983 periods. Only for demonstration projects (n=20) did median payback times decrease.

Measured vs. Predicted Savings

Of the projects in the data base, 30% included pre-retrofit predictions of energy savings, based on methods ranging from simple engineering estimates to sophisticated hourly computer models like DOE-2. Figure 6 shows actual, measured energy savings as a function of pre-retrofit predictions (normalized to floor area but **not** adjusted for post-retrofit changes in weather or operating hours - see below). Symbols are used to show the source of data and method of prediction. For all the groups except the "Hourly [computer modeling]" category, predictions were made using engineering estimates, monthly models based on the ASHRAE temperature-bin method, or other unspecified "audit" methodologies. With the exception of the post office group, Figure 6 shows a fairly even split between underestimates and overestimates of savings.

However, very few predictions (only 20 out of 128) came within 20% of the actual savings. The "hourly" predictions (made by Seattle City Light) both over- and underestimated savings, for a variety of reasons (see the discussion of submetered data, above). Data reported by the Center for Neighborhood Technology (CNT) and the Washington State Energy Office (WSEO) also included both over- and underestimated savings. In the ICP projects with estimated savings (located primarily in California) and the post offices, savings were consistently underestimated, for unknown reasons. In the University of California at Berkeley (UCB) buildings, savings from lighting retrofits were overestimated; increasing use of computers during the post-retrofit period was probably at least one source of discrepancy (see "Electricity Use and Office Equipment," below). Many unforeseeable circumstances can contribute to *overestimates* of savings, such as poor retrofit installation, lack of maintenance, or increasing process loads which obscure savings. One possible generic explanation for *underestimated* savings was reported by one of our data contributors, a consulting engineer who said that he consistently underestimates savings so that his clients will get more than they expect.

Persistence of Savings

Energy savings are typically tracked for only one year after retrofit. However, intentional or unintentional changes in building operation or other factors can significantly degrade savings. Half of the projects we looked at collected energy use data for two to four years after retrofit; these data are shown in Figure 7. (Note that each of the groups shown in Figure 7 is independent; the two-, three-, and four-year post-retrofit groups consist of different buildings.) In 60% of the projects, energy use continued to decrease in the years following the retrofit.[20] Energy savings in two-thirds of the retail stores increased after the first post-retrofit year; for other building types, savings increased in about half the cases. Changes in savings did not seem to correlate with the type of retrofit. For the projects with two and three years of post-retrofit data, energy intensity continues to decrease; however, energy use increased after the first year for the group of projects with four years of post-retrofit data. In all three cases, however, the changes in median energy intensity after the first post-retrofit year are smaller than the decrease in energy use associated with the conservation measure. For the projects which reported fuel and electricity use separately, it is interesting to note that median electricity use *increased* following the first post-retrofit year, for each of the subgroups. This is consistent with the view that growth in office equipment and other miscellaneous "plug" loads (see below) is responsible for at least part of the apparent "degradation" in energy savings over time.

FACTORS AFFECTING ENERGY USE AND SAVINGS

Many factors affect energy use in a building, and can therefore bias our interpretation of measured data on retrofit performance. Although it is not always possible to correct monitored energy use data to fully account for these factors, we need to be aware of their existence and potential impact on inferred energy savings. The following section discusses the effects of weather, hours of occupancy, and office equipment usage on energy consumption and retrofit savings.

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20 There may have been additional retrofits or changes in operation and maintenance that were not documented in the sources available to us.

Effects of Weather Normalization

Weather-adjustments of measured retrofit savings are being carried out with increasing frequency, especially by energy service companies and organizations working with small buildings. Although there is no generally accepted methodology for adjusting commercial building energy use for year-to-year changes in weather, one parametric study using data sets generated by the DOE-2 computer model, showed that relatively simple, degree-day-based normalizations may be as reliable as more complex, computer-simulation methods—at least for some commercial building types and climates (Eto, 1988). The energy consumption data presented in this report have *not* been adjusted for changes in weather, but many organizations we contacted did use weather adjustments in calculating savings. We examined the effect of these adjustments on total savings. Figure 8 shows the results, for four methods of weather-correction used by organizations that provided BECA data. For the projects which fall above the line labeled "weather-corrected = unadjusted," weather-correction has increased the apparent savings; savings were reduced by weather-correction for those below the line. The dashed lines represent a change in percentage savings of +10 *percentage points* or -10 percentage points, all based on pre-retrofit use. For example, if a project falls directly on the "+10%" line, and its unadjusted savings were 5%, then the weather-correction has increased savings to 15%. Both the magnitude and sign of this correction depends, of course, not only on the calculation method but also on the degree to which weather conditions differed between the pre- and post-retrofit year (and the "long-term average" year, if used), as well as on the fraction of total consumption which is (assumed to be) weather-dependent.

In the majority of cases, the change in percent savings after weather-correction was less than ten percent of pre-retrofit use; the largest correction was a twelve percent decrease. Of course, where retrofit savings are only a few percent to start with, weather-correction can have a noticeable effect on payback times. The Washington State Energy Office used the most sophisticated weather-correction method: a linear regression of variable-base heating and cooling degree-days. This method decreased savings in all four cases, by an average of seven percentage points. The Center for Neighborhood Technology used a weather-correction method which separated out a base consumption (equal to summer use) for both fuel and electricity, before applying an annual heating degree-day normalization factor to the remaining seasonal fuel use. Of the six projects weather-corrected this way, apparent savings increased in half the cases; the largest change was an increase of three percentage points. The Minnesota ICP program created an annual weather normalization factor (ratio of the long-term average heating degree-days to the heating degree-days for a particular year) for each of nine regions in the state. This correction factor was applied only to fuel consumption (not electricity). Weather-correction increased savings for 17 of the 20 projects for which data were available; on average, the increase was two percentage points. These cases illustrate the potential impact of weather adjustments on retrofit savings estimates. Further research is needed to verify and perhaps improve the reliability of weather-correction techniques, especially for space cooling energy use.

Hours of Occupancy

Although the number of hours of building operation (occupancy) is often cited as a major factor affecting energy use and savings, these data (pre- and post-retrofit) were not reported for most of the buildings in our data base. Nor are the concepts of operating hours (which may differ from "occupied" hours) very well-defined in most cases. However, weekly hours of occupancy during the pre-retrofit period were reported for 14 schools and 23 office buildings. The elementary and secondary schools were occupied for 40 to 55 hours/week, while the colleges had significantly longer occupancy hours (90 to 130 hours/week). Occupied hours for offices, where reported, varied from 40 to 80 hours/week. We examined the relationship between pre-retrofit energy intensity and hours of occupancy, and found no clear pattern, for this small sample of buildings. It is likely that variations in location and process loads had a stronger influence on energy intensity than did operating hours. A similar conclusion emerges from the partial data published from the 1986 NBECS survey, on energy intensity as a function of operating hours (EIA, 1989b). For all commercial buildings together, there is a general trend for energy intensity (of both electricity and natural gas) to increase with longer hours of operation, but there are several anomalies. Other factors such as building size and type, sometimes strongly correlated with hours of operation, may explain some of the variation in energy intensities. Also, operating hours may not be reported accurately, or variations from week to week, among different zones in the building, or by type of end-use equipment (e.g., lights vs. HVAC), may all confound the use of a single value to represent "operating hours." For the future, it is important to be more precise about definitions and also to document changes in operating hours that coincide with the retrofit period and may help to explain observed changes in energy use—or the absence of expected changes.

Electricity Use and Office Equipment

Changes in electric and associated thermal (HVAC) loads from office equipment and other miscellaneous "plug loads" is another factor often mentioned as complicating the inference of retrofit savings from monitored, whole-building energy use. In office buildings, in particular, these loads are often ignored or relegated to the "other" category, even though they often represent a larger load than many widely recognized and carefully monitored end-uses, such as outside night lighting or water heating. In some new office buildings, the "office information services" end-use (computers, peripherals, printers, etc.) can represent 20-25% of total electricity consumption, and a load that at 1-2 W/ft^2 (or more) can equal or surpass the load of interior electric lighting (Norford, et al., 1988).

Often, when whole-building energy use fails to decrease as predicted after a retrofit, or steadily increases, the tendency is to blame the result on increased electric loads from new or upgraded computers and other office equipment, more intensive use of existing equipment, and the associated impacts on HVAC energy.[21] In one retrofit project at a large classroom building

[21] As with thermal loads from lights, the general tendency would be for office equipment loads to reduce heating energy requirements and increase cooling and fan energy. However, the actual effects in a real building may be more complex, due to other heat gains from equipment, people, and solar transmission; HVAC equipment zoning; sizing and part-load efficiencies; control settings; and the differences between heating or cooling profiles by time-of-day, and the timing of internal heat loads from office equipment. These issues deserve more careful analysis with computer models, but generally, one might expect increased office equipment thermal loads, in most commercial buildings, to add more to cooling and fan energy than they save in heating energy.

on the University of California, Berkeley campus, we have carefully documented the changes in computers and other office equipment loads, using University equipment purchasing records and a range of estimates of operating profiles for different types of equipment. The results are shown in Figure 9, which traces whole-building electricity use,[22] both unadjusted and adjusted for changes in office equipment, over a seven-year period, spanning two retrofit cycles. According to the first set of bars in the figure, total (unadjusted) electricity use has increased steadily since 1983, despite extensive lighting retrofits in 1982, 1983, 1986, and 1987. However, after accounting for the impact of changes in office equipment (under either high-use or low-use scenarios), the effects of the lighting retrofits become apparent. A more accurate estimate of office equipment loads would require, in addition to the inventory data used in this case, either extensive submetering or carefully sampled observations of actual usage profiles.

EVOLVING PERSPECTIVES: FROM "RETROFIT" TO "ENERGY MANAGEMENT"

Energy conservation is often approached as a one-time alteration to a building. An energy auditor recommends the appropriate retrofits; once these are installed, the building is deemed to be "energy efficient." This view ignores the possibility of problems with retrofit installation or subsequent building operation—as well as future energy-saving opportunities that may accompany technological advances, building renovation, changes in tenancy, etc. The unfortunate result is that too many buildings fall well short of their energy conservation retrofit potential, while the measures that are installed often fail to perform as they should.

A different approach was taken by the Washington State Energy Office (WSEO), which followed up on a number of buildings retrofitted under Bonneville Power Administration's Institutional Buildings Program. WSEO staff collected and analyzed post-retrofit consumption data, and visited each site to inspect the installation. They found a number of easily correctable problems, like time clocks which had defaulted to factory settings following a power outage, and energy management systems that were improperly set and operated (see case study WSE001 in Appendix B). Such "retrofit commissioning," in which the installed retrofit is inspected and tested to ensure correct operation, would undoubtedly address part of the problem. However, even properly installed and calibrated measures can eventually be disabled through lack of maintenance, inappropriate usage, or other factors.

All this leads us to conclude that energy management must be viewed, not as an event but rather as a *process*—one that incorporates both an understanding of proper building operation on the part of the facility manager and the long-term tracking of energy performance and specific indicators of operating problems.

Two examples illustrate how such a process could be implemented. At the Amoco Corporate Headquarters in Chicago, both conservation measures and maintenance activities have been carried out almost continuously since the building's construction in 1972. A skilled in-house maintenance crew, directed by a building manager with a good understanding of the

[22] Excluding heating and (absorption) air conditioning, which are provided through the campus central steam system.

building's behavior, have reduced the structure's consumption by over 40%, with a payback time of about six years (see case study AJ0013 in Appendix B). In another case, researchers examined two large Department of Energy office buildings and produced daily graphs of hourly demand to help the building staff identify operation problems. Solely through improved maintenance practices, energy consumption in both structures was reduced by 10%, despite increases in electricity use attributed to the proliferation of computer equipment (see case study DOE001 in Appendix B). These examples point out the need for increased attention to building system operations and the usefulness of ongoing tracking of energy consumption to identify problem areas.

ESTIMATING THE STOCK-WIDE CONSERVATION POTENTIAL FROM MEASURED DATA

Estimates of potential conservation savings in the U.S. commercial stock have been developed by a number of sources (SERI, 1981; MacDonald, 1986; MacDonald, et al., 1986; CEC, 1988; DOE, 1989; NWPPC, 1989). Such characterizations of conservation potential are useful in helping to guide future conservation research, programs, and private investments, as well as providing feedback on the aggregate savings that have been achieved. However, all estimates to date of commercial sector energy conservation potential have relied primarily on engineering estimates or computer simulation, rather than measured data on actual retrofit savings. An estimate based on measured energy savings is more reliable, because it reflects performance of conservation measures under actual installation and operating conditions.

Some preliminary estimates of conservation potential based on measured data have been carried out, using BECA data for new single-family and retrofitted multifamily residences (Meier, et al., 1988). Since the BECA databases are not statistically representative of the U.S. building stock, extrapolation from BECA case studies to stockwide energy savings potential is not a straightforward task. Rather than defining prototype structures and modeling the effects of various conservation options (as is typically done in conservation-potential studies), estimates based on measured data require a different approach. First, the BECA database must be compared to the relevant stock segment, in terms of building type, applicability of conservation measures (i.e., what measures have already been installed, and which are physically possible), and initial energy intensities by end-use. Finally, depending on the quality of measured data available, the savings potential from specific retrofit measures, or from typical retrofit "packages," may be estimated.

We have not yet developed such estimates for commercial sector retrofits, due to limitations in both the BECA data base and the characterization of the U.S. stock. Measured BECA data are lacking on retrofits in most types of retail buildings and in smaller commercial buildings in general (less than 50,000 ft^2). There are still only very limited data on measured energy savings from individual retrofit measures in commercial buildings, and on cases that demonstrate the full potential for cost-effective retrofits. As better data become available, we expect to conduct follow-up studies that assess the potential for energy management in the commercial sector based on inferences from measured data.

However, there are a number of indicators which suggest substantial remaining opportunities for conservation in the commercial sector:

- As noted earlier, typical investment levels are modest (\$0.56/ft^2 or 8 months of energy cost) and payback times relatively short (3.1 years) for retrofits in the BECA data base (Table 2).
- Even after retrofit, energy intensities in the buildings documented in BECA remain higher than the corresponding medians for the U.S. building stock, and well above those of energy-efficient new buildings (Figure 1).
- Published data from the NBECS survey indicate that large fractions of the U.S. commercial stock have not yet been audited, or had even simple and widely-available conservation measures installed (see Table 5). This is particularly true for smaller buildings, buildings that are leased rather than owner-occupied, and for lighting system improvements and controls.

CONCLUSION

Overall results on the measured savings and cost-effectiveness of commercial sector retrofit measures, by building type and project sponsor, were summarized in Table 2. For the 447 retrofit projects now in the BECA-CR data base, median energy savings were 18% of whole-building consumption, median retrofit investments \$0.56/ft^2, and the median simple payback time 3.1 years. Retrofits focusing on HVAC and/or lighting systems had typical payback times of one to three years, while packages that included shell retrofits had median paybacks of 5-9 years. Recently implemented retrofits were more expensive and resulted in lower savings and longer payback times than conservation measures installed prior to 1983. Despite this indication that more of the cost-effective savings potential is being achieved, post-retrofit energy intensity for buildings in the data base was still higher than that of the stock average, and much higher than that of new commercial buildings designed to be energy-efficient. In addition, a number of studies indicate that optimum savings are not being achieved for every conservation dollar invested, due to improper retrofit installation and/or maintenance. A comprehensive understanding of energy management as a process is needed, including inspection of installed retrofits and ongoing tracking of energy consumption as an indicator of operation problems.

We have identified research needs in a number of areas related to retrofit selection, monitoring, and data analysis methods. Data on savings from individual retrofits are still sparse, although more extensive use of submetering is beginning to answer questions regarding cost-effectiveness, particularly for lighting measures. More consistent reporting of the components of electricity costs, especially demand and time-of-use charges, would make it possible to incorporate load-shifting measures when calculating cost-effectiveness. Further research is needed on the appropriateness of short-term submetering for different building and retrofit types, and how best to extrapolate from short-term savings to long-term cost-effectiveness. Submetering also helps to isolate factors other than the retrofit measures which can influence building energy performance. Further study is needed of the effects on energy use of weather, occupancy, and changes in equipment loads, for different building types. Measured savings from conservation retrofits in retail stores and small buildings are severely lacking, as are data on long-term performance and operating costs of various measures, especially those affecting lighting, HVAC systems, and controls. Further work in these areas will allow us to develop more reliable, detailed estimates of the remaining conservation potential in U.S. commercial buildings. Such information will help policy makers to decide how much of our future energy needs can be supplied through improved energy efficiency, and what level of public and private resources should be devoted to mobilizing that conservation potential.

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Table 1. Building characteristics of BECA database vs. 1986 U.S. stock.

Building Type	*% of Buildings* [a] *BECA*	*% of Buildings* [a] *U.S. Stock* [b]	*BECA* *BECA*	*BECA* *U.S. Stock* [b]
- Education	46	6	43	13
Elementary	28	-	15	-
Secondary	13	-	22	-
Colleges	5	-	6	-
- Health Care	7	1	14	4
Hospitals	4	-	4	-
Other	3	-	10	-
- Offices	17	15	15	16
Small (≤ 50,000 ft^2)	5	14	< 1	8
Large (> 50,000 ft^2)	12	1	14	8
- Retail (non-food)	22	31	22	22
Post Offices	21	-	22	-
- Food Sales/Service	< 1	8	< 1	3
- Other (assembly)	3	14	< 1	13
- Other (lodging)	2	3	1	5
- Other (warehouses)	< 1	13	<1	15
- Other (unspecified)	3	5	5	7
Energy Sources Used:				
- All Electric	12	23	6	23
- Fuel and Electric	88	77	94	77
Size:				
- < 5000 ft^2	2	53	< 1	11
- 5-10,000 ft^2	4	22	1	12
- 10-25,000 ft^2	10	13	5	16
- 25-50,000 ft^2	15	6	13	15
- 50-100,000 ft^2	20	3	17	15
- 100-200,000 ft^2	25	1	25	12
- 200-500,000 ft^2	17	1	19	12
- > 500,000 ft^2	6	< 1	20	8
Region:				
- Northeastern U.S.	34	16	34	20
- Midwestern U.S.	25	26	34	28
- Southern U.S.	15	38	13	33
- Western U.S.	24	20	16	19
- Canada	1	-	2	-
- Europe	1	-	1	-
Year Built: [c]				
- ≤ 1920	14	11	8	10
- 1921-45	24	15	35	15
- 1946-60	18	21	14	17
- 1961-73	35	24	36	27
- 1974-79	10	14	6	14
- ≥ 1980	< 1	15	< 1	17

[a] BECA data are for one or more buildings per retrofit "project" (typically, multiple buildings are on a single meter at one site). The BECA data include a small number of non-U.S. buildings, in Canada and Europe (2% of the total).

[b] Source: EIA, 1988. The NBECS stock data are for all U.S. buildings, not only those reported as retrofitted. The BECA data set includes 9 retrofitted buildings from outside the U.S.: 5 from Canada, 3 from Sweden, 1 from France.

[c] About half of the projects in BECA did not report the year built. Percentages shown here are only for projects reporting year built.

Table 2. Summary of energy savings and economic indicators.[a]

	Number of Projects	*Site Energy Savings*[b] *(kBtu/ft²-year)*	*(%)*	*Elec. Savings (kWh/ft²-year)*	*Fuel Savings (kBtu/ft²-year)*	*Retrofit Cost (1988 \$/ft²)*	*Payback*[c] *Time (years)*	*CCE Site*[d] *(1988 \$/MBtu)*	*CCE Resource*[e] *(1988 \$/MBtu)*
All Buildings	451	20 ± 2	18 ± 1	0.7 ± 0.2	12 + 1	0.56 ± 0.05	3.1 ± 0.5	3.10 ± 0.40	2.30 ± 0.30
- All-electric only	54	16 ± 3	22 ± 3	4.6 ± 1.0	0	0.75 ± .19	2.9 ± 0.9	9.20 ± 2.60	2.70 ± 0.80
Buildings with savings>0	406	23 ± 2	20 ± 1	0.9 ± 0.2	15 ± 2	0.57 ± 0.06	2.6 ± 0.3	2.80 ± 0.30	2.00 ± 0.20
- All-electric only	51	17 ± 3	22 ± 3	4.9 ± 1.0	0	0.74 ± 0.21	2.7 ± 0.9	8.50 ± 2.50	2.50 ± 0.80
By Building Type:									
Education	207	16 ± 2	16 ± 2	0.2 0.1	14 ± 2	0.61 ± 0.08	5.3 ± 1.2	3.10 ± 0.70	2.70 ± 0.60
- All-electric only	10	15 ± 4	26 ± 7	4.2 ± 1.3	0	1.08 ± 0.22	5.8 ± 1.6	15.50 ± 4.90	4.60 ± 1.40
Health	29	37 ± 13	15 ± 4	0.1 ± 0.6	37 ± 12	1.10 ± 0.30	5.9 ± 4.5	4.20 ± 1.90	3.50 ± 2.10
Office	74	22 ± 4	23 ± 3	2.4 ± 0.6	6 ± 3	0.81 ± 0.23	2.6 ± 1.5	5.10 ± 1.90	2.20 ± 0.80
- All-electric only	23	13 ± 7	17 ± 7	3.8 ± 2.1	0	0.83 ± 0.39	4.6 ± 3.9	13.90 ± 5.80	4.10 ± 1.70
Retail	101	24 ± 2	21 ± 2	4.0 ± 0.7	5 ± 2	0.36 ± 0.04	1.0 ± 0.2	2.10 ± 0.50	1.00 ± 0.30
- All-electric only	15	26 ± 6	22 ± 4	7.7 ± 1.8	0	0.55 ± 0.19	1.0 ± 0.6	3.10 ± 2.20	0.90 ± 0.70
Other	40	25 ± 7	15 ± 4	1.5 ± 0.9	15 ± 7	1.10 ± 0.50	7.1 ± 3.1	4.40 ± 7.30	3.50 ± 1.30
By Project Sponsor:									
Owner-paid	282	20 ± 2	18 ± 1	1.2 ± 0.3	10 ± 1	0.45 ± 0.06	1.5 ± 0.3	2.60 ± 0.50	1.50 ± 0.30
- All-electric only	37	20 ± 5	22 ± 4	5.9 ± 1.6	0	0.56 ± 0.21	1.9 ± 0.9	7.60 ± 2.30	2.30 ± 0.70
ICP-funded	96	14 ± 3	12 ± 2	0.1 ± 0.1	14 ± 3	0.56 ± 0.10	6.5 ± 14.2	4.10 ± 1.20	3.40 ± 2.00
Other grants	49	39 ± 9	33 ± 4	0.8 ± 0.7	38 ± 10	1.09 ± 0.18	3.4 ± 1.4	2.70 ± 1.10	2.20 ± 0.60
- All-electric only	8	12 ± 5	14 ± 5	3.4 ± 1.4	0	1.76 ± 0.36	11.1 ± 3.6	32.60 ± 11.90	9.70 ± 3.50
Demonstration projects	24	20 ± 8	23 ± 7	1.6 ± 0.8	3 ± 7	0.99 ± 0.28	6.8 ± 8.9	6.20 ± 2.40	3.80 ± 3.80
- All-electric only	9	11 ± 2	17 ± 7	3.2 ± 0.7	0	1.02 ± 0.26	4.1 ± 1.4	12.60 ± 3.70	3.70 ± 1.10

[a] Values given are medians ± standard errors, unless the number of projects is less than or equal to 10, in which case averages are used.

[b] Electricity savings are converted to site energy using 3413 Btu = 1 kWh.

[c] Simple payback time is calculated using national average energy prices (see text).

[d] CCE: Cost of Conserved (site) Energy; electricity savings are converted to site energy using 3413 Btu = 1 kWh.

[e] Electricity savings are converted to resource energy using 11,500 Btu = 1 kWh.

Table 3. Savings and cost-effectiveness of individual retrofit measures.[a]

Retrofit Measure	*Number of Projects*	*Energy Savings[b]*		*Retrofit Cost (1988 \$/ft^2)*	*Simple Payback Time[c] (years)*	*CCE (Site)[d] (1988 \$/MBtu)*	*CCE (Resource)[e] (1988 \$/MBtu)*
		(kBtu/ft^2-year)	*(%)*				
Lighting Controls	8	18 ± 4	19 ± 3	0.55 ± 0.34	3.7 ± 2.7	4.60 ± 2.30	4.10 ± 2.90
Window Modifications	5	6 ± 5	6 ± 5	0.49 ± 0.17	n/a[f]	n/a[f]	n/a[f]
Local HVAC Controls	7	9 ± 7	8 ± 5	0.25 ± 0.17	n/a[f]	n/a[f]	n/a[f]
Energy Mgmt. Systems	13	15 ± 9	13 ± 9	0.33 ± 0.08	11.2[g]	7.80[g]	7.10[g]

[a] Values given are averages ± standard errors, except when the number of projects is greater than ten, in which case medians are listed.

[b] Electricity savings are converted to site energy using 3413 Btu = 1 kWh.

[c] Payback time is calculated using national average energy prices.

[d] CCE: Cost of Conserved Energy; electricity savings are in site energy using 3413 Btu = 1 kWh.

[e] Electricity savings are converted to resource energy using 11,500 Btu = 1 kWh.

[f] For both of these retrofit measures, only four projects reported retrofit costs, and only two of these had positive energy cost savings and, therefore, payback times and CCEs.

[g] Three projects had negative energy savings; therefore the standard error of the cost-effectiveness indicators cannot be calculated.

Table 4. Trends in simple payback time, by year of retrofit.

Year of Retrofit	Simple Payback Time (years)									
	All projects		Owner-paid		ICP		Other grants		Demo.	
pre-1978	1.6	*(n=74)*	1.5	*(n=50)*	--		1.1	*(n=12)*	7.3	*(n=11)*
1979-80	1.2	*(n=159)*	1.0	*(n=148)*	--		4.5	*(n=8)*	--	
1981-82	3.0	*(n=127)*	1.6	*(n=51)*	4.8	*(n=63)*	2.3	*(n=7)*	--	
1983 on	7.7	*(n=95)*	5.1	*(n=35)*	18.3	*(n=29)*	8.8	*(n=22)*	2.5	*(n=9)*

Table 5. Energy audits and conservation measures in the 1986 U.S. commercial building stock.

	Percent of Floor Area				
	Audited	With any Conservation Measure	With any Envelope Measure	With any HVAC Measure	With any Lighting Measure
All Commercial Bldgs.	28	94	89	72	57
- Large Buildings (> 100,000 ft^2)	45	98	92	88	78
- Small Buildings (< 1,000 ft^2)	11	88	84	51	32
- Government-owned	47	95	87	84	66
- Rented or Leased	11	94	90	67	54
- Newer Buildings (1980+)	18	97	96	77	71

Source: 1986 NBECS - Non-Residential Buildings Energy Consumption Survey (EIA, 1988 and EIA, 1989b).

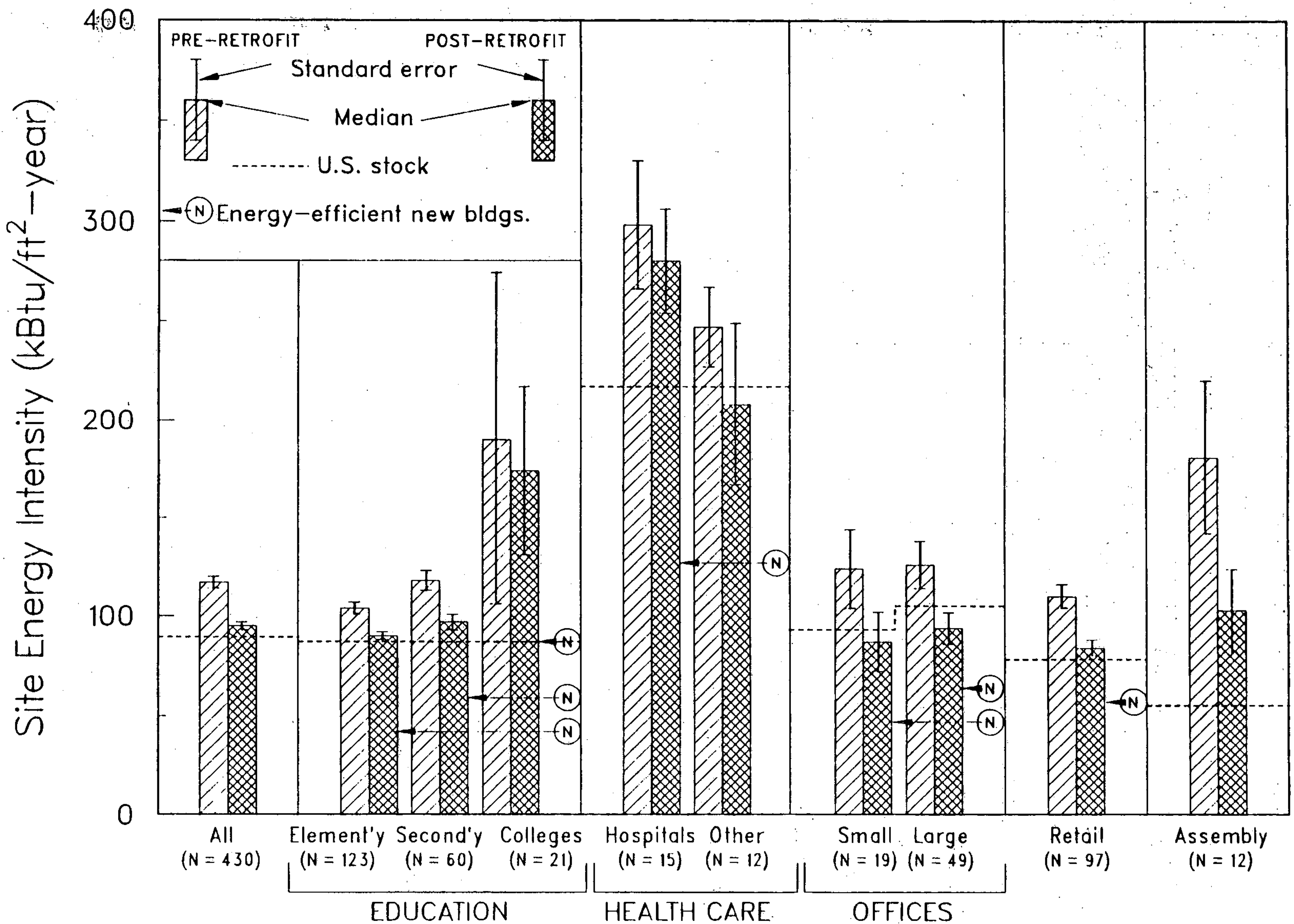


Figure 1. Pre- and post-retrofit whole-building energy intensity for subsets of the BECA-CR database. For definitions of building types, see section on "Building Characteristics and Stock Comparison" in text. "U.S. Stock" consumption represents average usage for the applicable building type as of 1986 (Source: EIA, 1989b). For comparison, we also show measured energy consumption, by building type, for a limited number of **new** buildings designed to be energy-efficient; these are typical values derived from the BECA-CN data base (Piette and Riley, 1986). The values for new hospitals and retail buildings are based on very small samples.

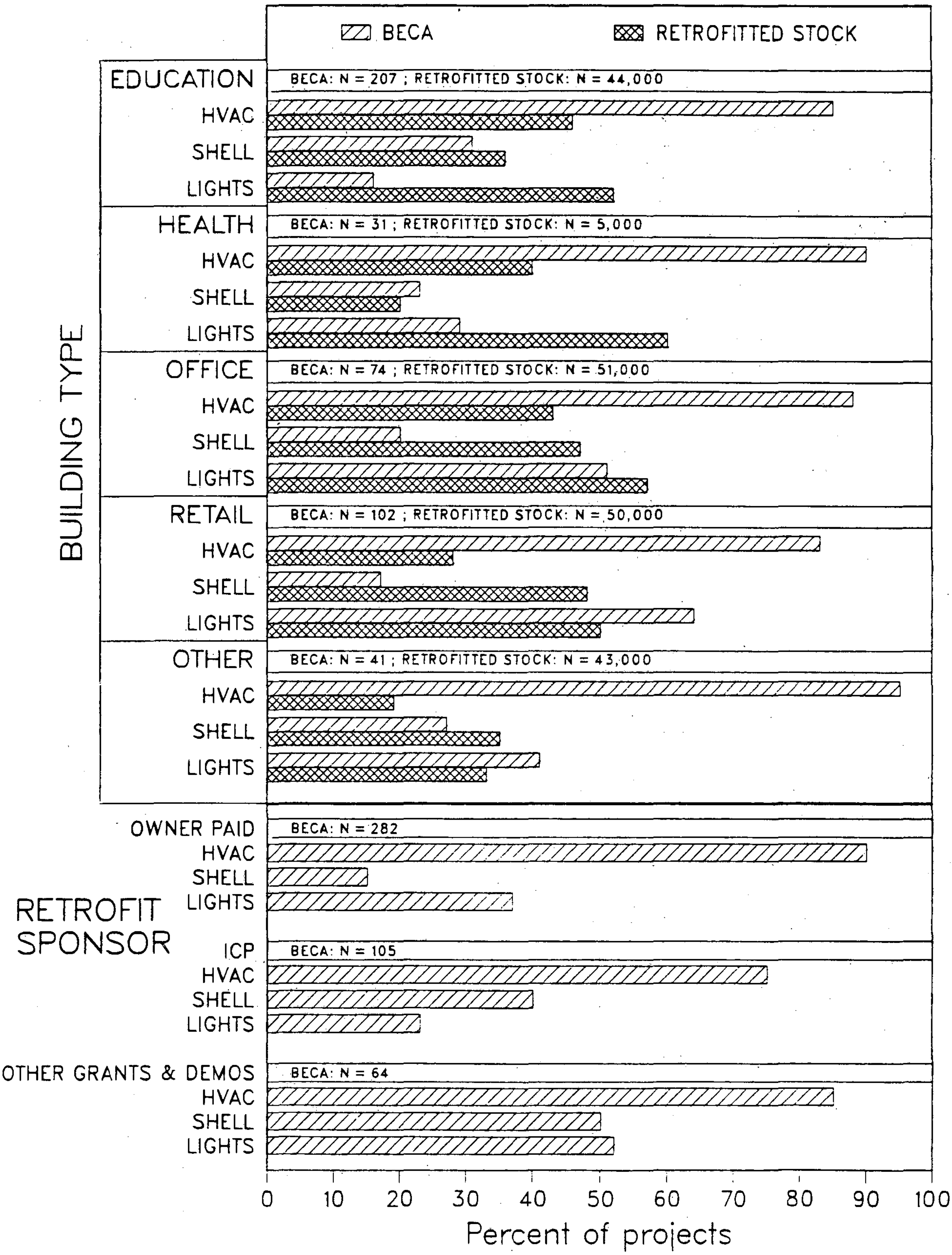


Figure 2. Frequency with which retrofits were installed in BECA projects, compared with the retrofitted U.S. stock, by general retrofit category: "HVAC," "Shell," and "Lights." The total number of retrofits is shown in the uppermost bar for each category. Note that, for each building type, the total percentage for the three retrofit categories is greater than 100%, because several measures are often installed in an individual building. For the U.S. stock, retrofits (as of 1986) actually represent only those conservation measures *added after audits* (EIA, 1988); data on total retrofit activity are not published at this time.

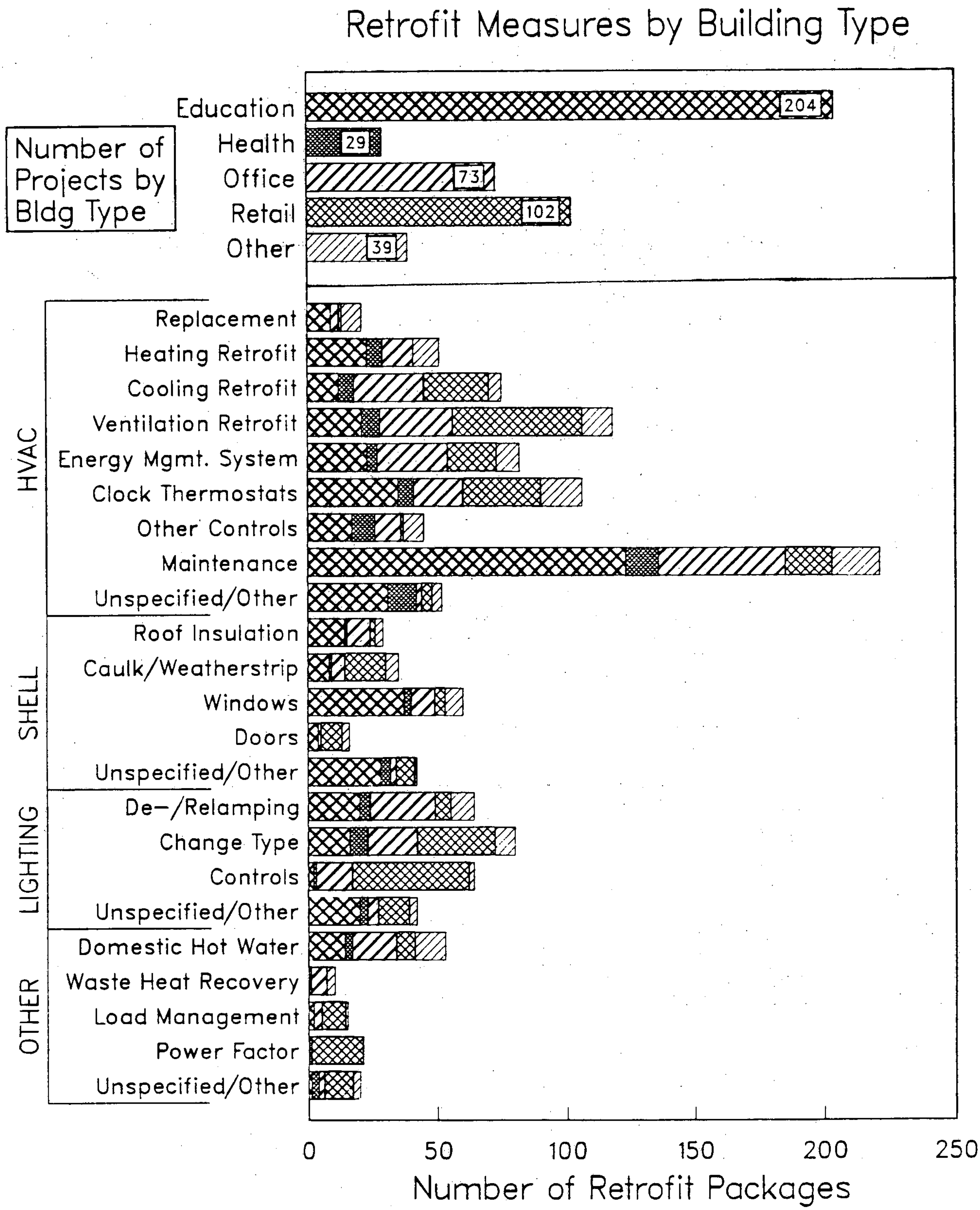


Figure 3. Frequency with which individual retrofit measures were installed in educational, health, office, retail, and other commercial buildings. The total number of retrofit projects, by building type, is shown at the top; the same shading pattern is repeated for each retrofit measure, to show that measure's distribution by building type. Note that, for a given building type, the total of retrofit measures is greater than the total number of projects, due to multiple measures installed in many buildings. Buildings retrofitted under the Institutional Conservation Program were often aggregated by general retrofit type (HVAC, Shell, or Lighting); these projects appear in the "Unspecified/Other" category for each retrofit type.

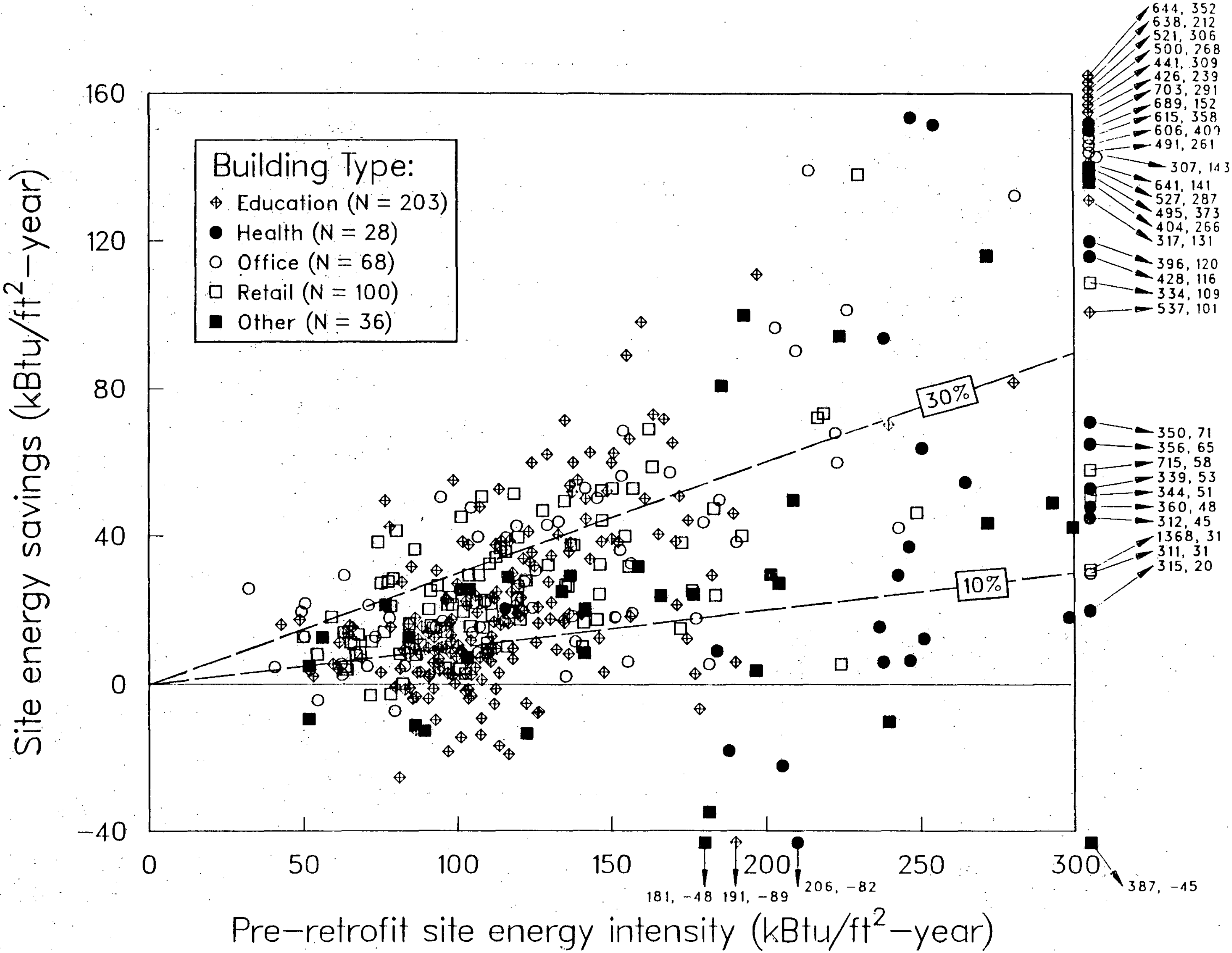
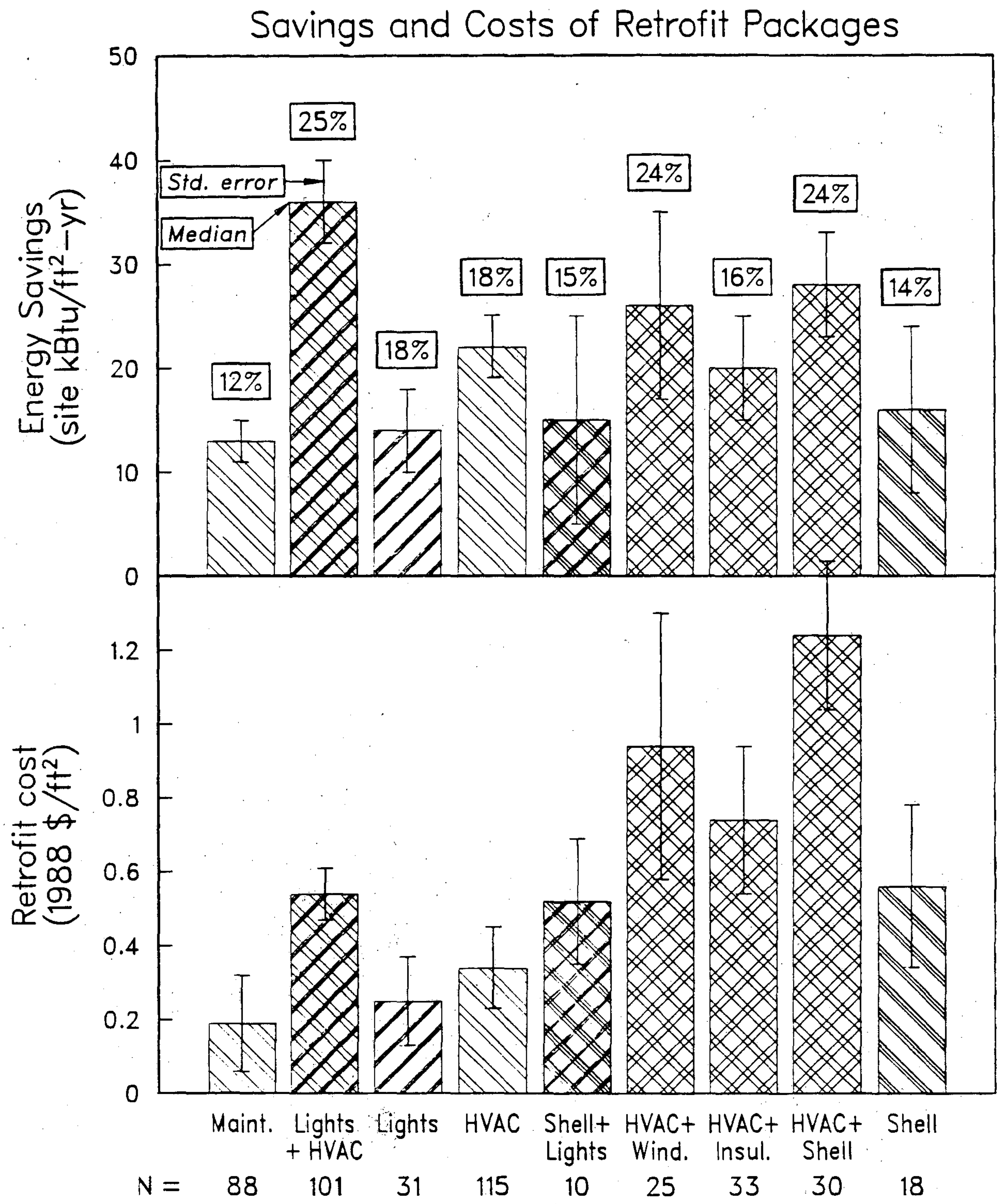


Figure 4. Energy savings as a function of pre-retrofit whole-building energy intensity, grouped by building type. Electricity use is expressed in terms of site energy (3413 Btu=1 kWh). The dashed lines show percentage savings of 10% and 30%.



Payback time (yrs)	1.1	1.4	2.0	2.9	4.7	5.7	6.2	6.7	8.6
CCE ($/site MBtu)	1.70	2.50	4.80	2.70	2.60	3.90	3.60	5.20	4.30
CCE ($/res. MBtu)	0.90	0.90	2.80	2.30	2.20	2.70	3.60	3.40	4.00

Figure 5. Energy savings, retrofit cost, median payback times (using national average energy prices), and costs of conserved energy of various retrofit strategies in commercial buildings. Each project is assigned to the narrowest retrofit category which encompasses all retrofit measures. "Maint." retrofits are changes in maintenance practices only. "Shell," as used here, refers to changes to both window measures, improved insulation, and infiltration reduction. Minor lighting retrofits also took place in some of the buildings assigned to the "HVAC + Wind.," "HVAC + Insul.," and "HVAC + Shell" categories.

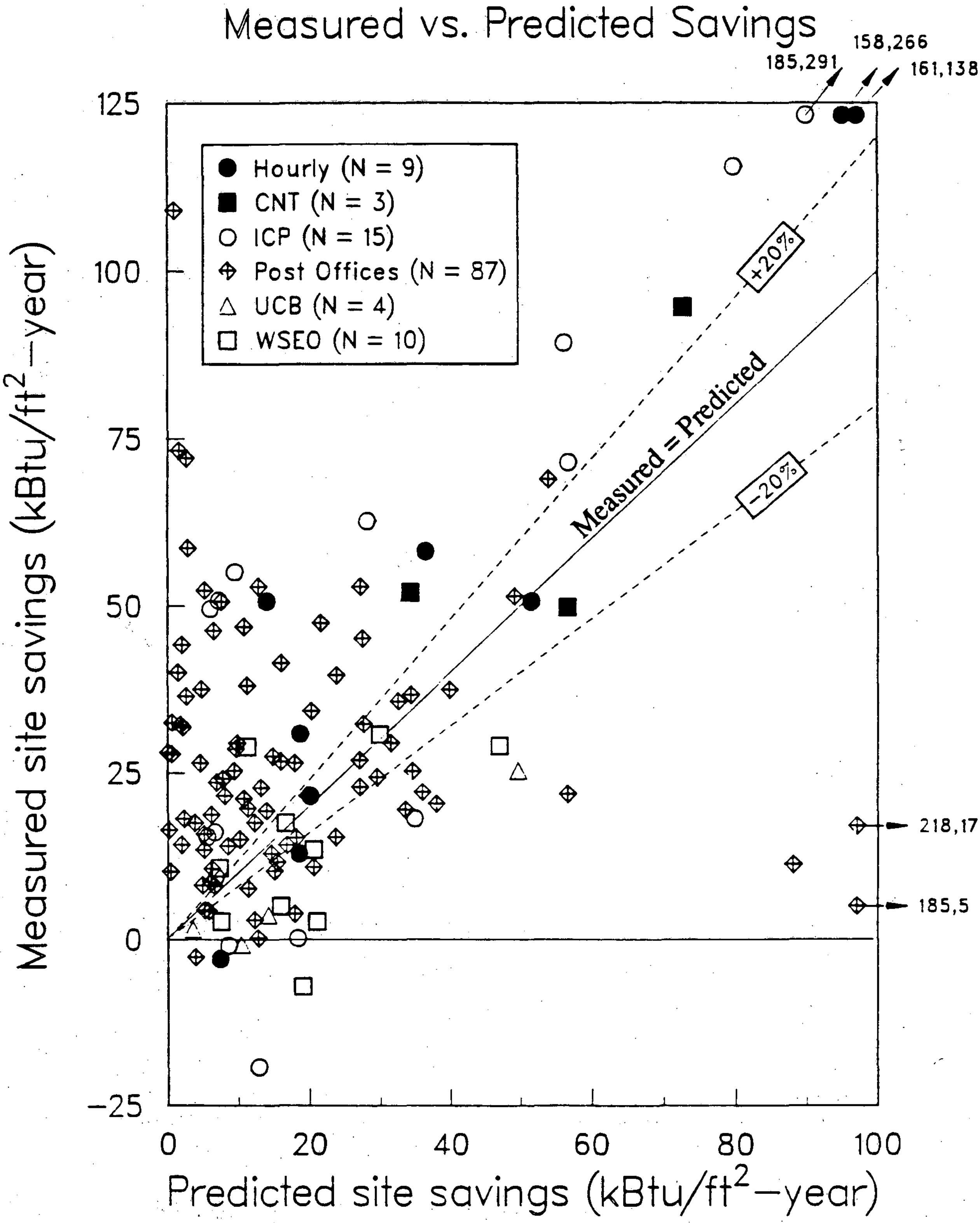


Figure 6. Measured vs. predicted savings for commercial building retrofits. "Hourly" predictions were made using tools such as DOE-2. The other data sets, grouped by project sponsor, were based on less sophisticated methods such as engineering estimates, monthly models based on the ASHRAE bin method, or unspecified "audit" methodologies. "CNT" buildings were retrofitted by the Center for Neighborhood Technology, "ICP" is the Institutional Conservation Program, "Post Offices" are U.S. Postal Service buildings, "UCB" are buildings on the University of California at Berkeley campus, and "WSEO" buildings were studied by the Washington State Energy Office.

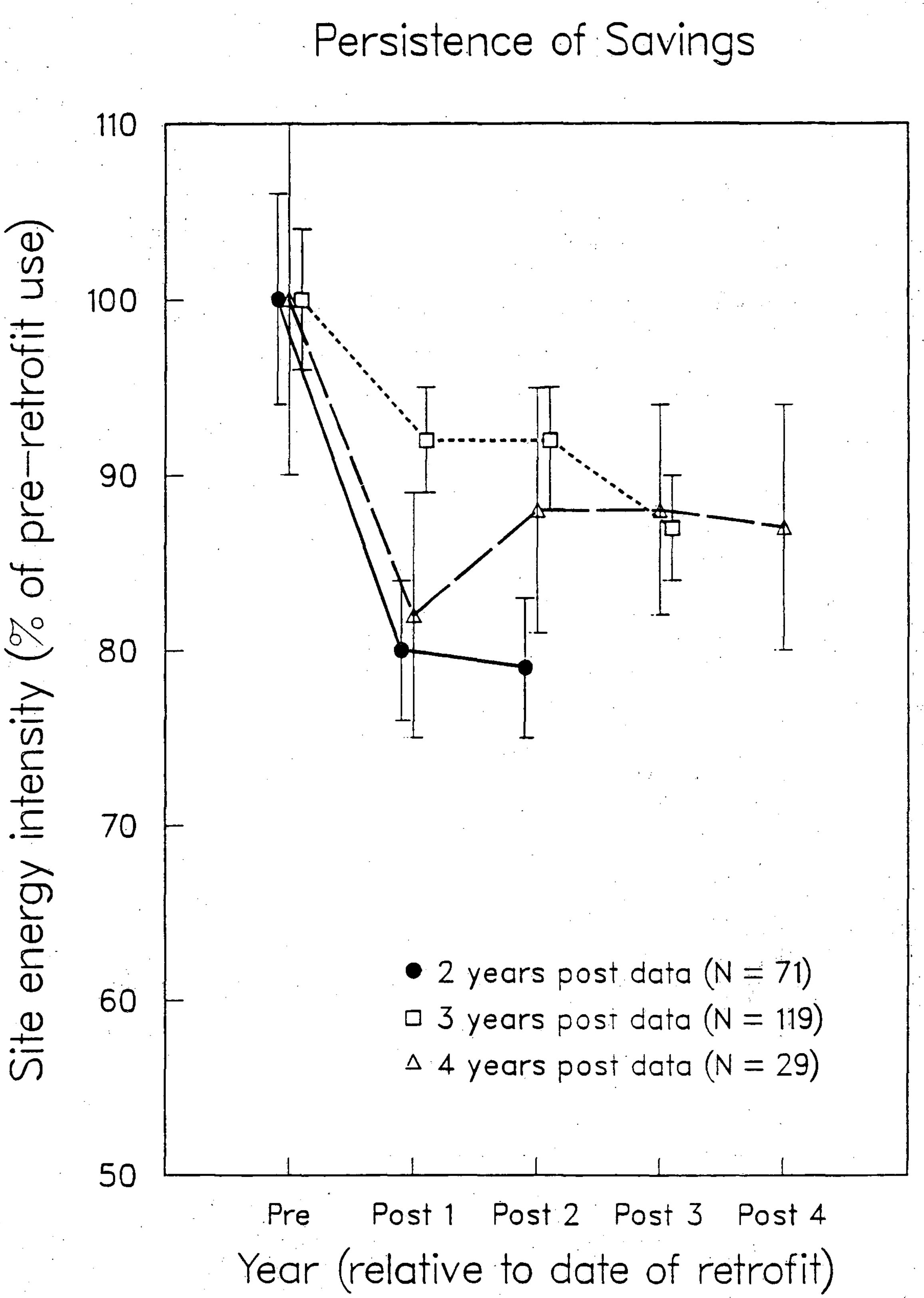


Figure 7. Persistence of energy savings for several years following retrofit installation. Note that each of the subgroups is independent; the two-, three-, and four-year groups consist of different buildings. For the projects with two or three years of post-retrofit data, energy use continued to decline, while consumption in projects with four years of post-retrofit data increased after the first post-retrofit year.

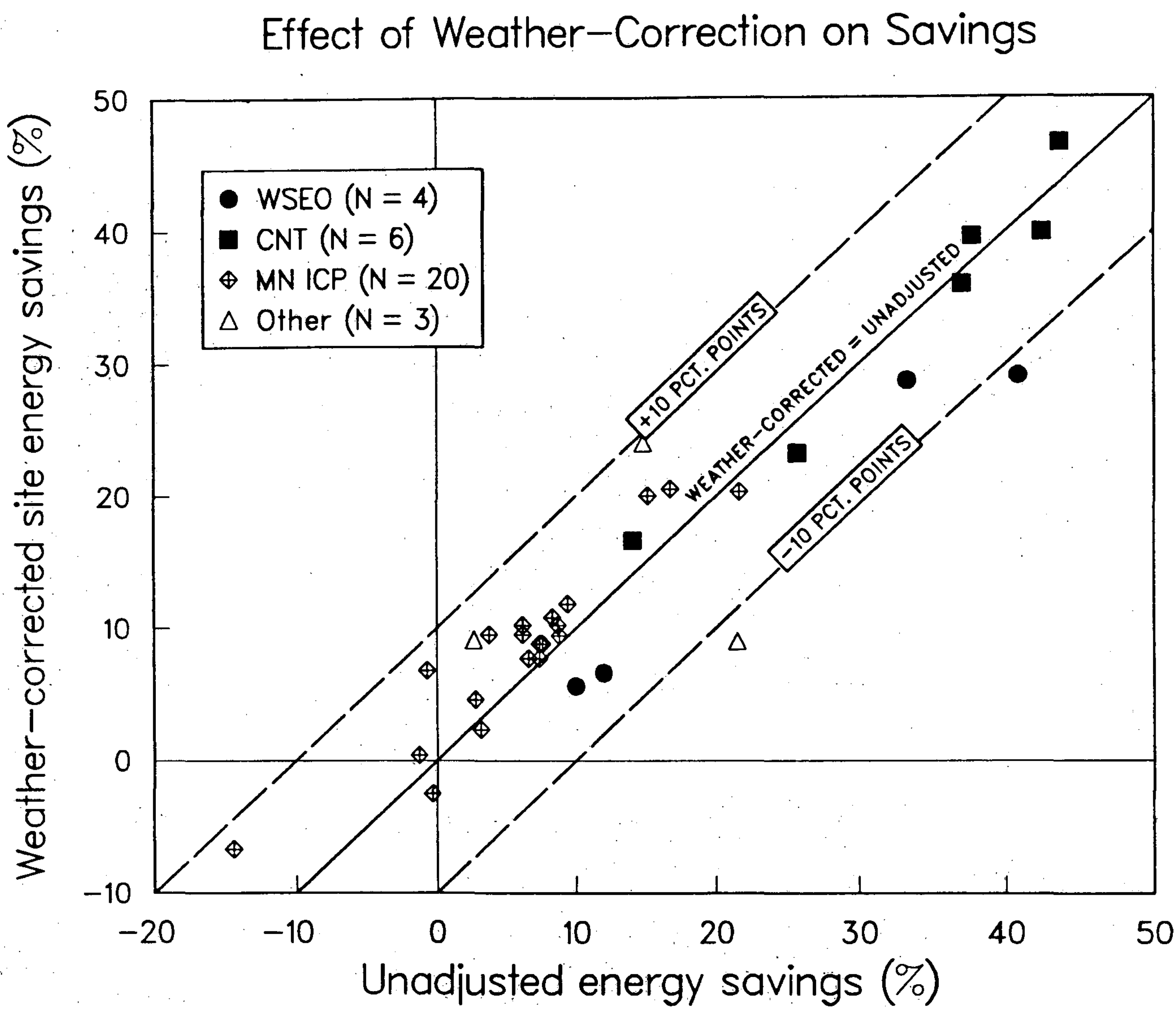


Figure 8. Effect of weather-correction on percentage energy savings. Weather-corrected savings are plotted as a function of unadjusted savings, both expressed as a percent of pre-retrofit use. The dashed lines represent a change in percentage savings of +10 *percentage points* or -10 percentage points, all based on pre-retrofit use. "WSEO" are data from the Washington State Energy Office, which performed a linear regression of monthly energy usage on variable-base heating and cooling degree-days. "CNT" data are from the Center for Neighborhood Technology, which scaled weather-dependent fuel use by the ratio of long-term average to actual heating degree-days (base 65°F). "MN ICP" are data from the Minnesota Institutional Conservation Program, which scaled all non-electric usage by the ratio of normal to actual heating degree-days (base 65°F). "Other" buildings data are based on a scaling of whole-building energy consumption by the ratio of long-term average to actual heating degree-days (base 65°F).

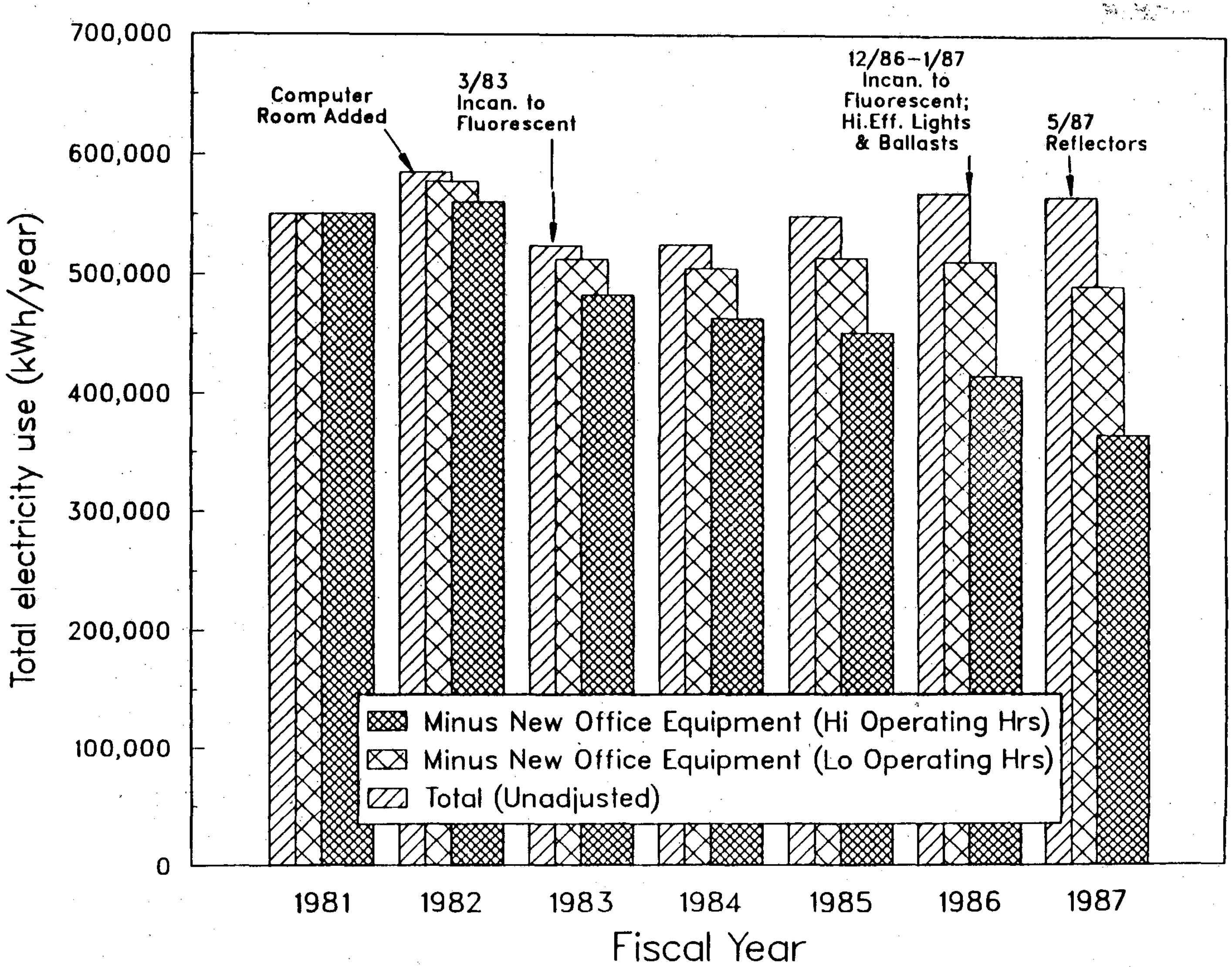


Figure 9. Effects of lighting retrofits and changes in office equipment on electricity use in a classroom building at the U.C. Berkeley campus. The left-hand bar in each cluster shows the "raw" (unadjusted) whole-building electricity use for that year. The next two bars show two estimates of adjusted electricity use, after accounting for the increase in computers and related office equipment (at low and high usage levels, respectively). Total (unadjusted) electricity use has increased steadily since 1983, despite extensive lighting retrofits in 1982, 1983, 1986, and 1987. After accounting for the impact on electricity loads of changes in office equipment, the effects of the lighting retrofits become apparent.

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