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MONITORED ENERGY PERFORMANCE OF NEW AND RETROFITTED RESIDENTIAL BUILDINGS: RESULTS FROM THE "BECA" DATA BASE *

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ABSTRACT

We summarize measured energy performance data, drawn from the "BECA" data base at LBL, on several hundred new and retrofitted residences. We explore the two-way relationship between occupant behavior and the physical characteristics and energy performance of residential buildings. A more detailed, empirical understanding of both physical and occupancy variables is needed to help explain the observed variance in energy performance among physically similar houses, as well as the variance between performance predictions and actual measurements. Physical and occupancy factors may be difficult to separate, in theory as well as in practice. The evaluation of "occupant effects" raises questions not only of insufficient data, but of inadequate definition of the outputs resulting from energy use: occupant comfort, well-being, and other "building services." Thus, energy efficiency is properly defined not as reduced consumption, but as a change in the ratio of energy used to services obtained. A concluding section discusses some implications, both for research and for energy conservation policy and programs, of a broadened perspective that embraces both physical and occupant effects on building energy performance.

KEYWORDS: Residential Energy Conservation, Retrofitting, Monitoring, Consumer Behavior

(FRENCH ABSTRACT)

Consommations énergétiques mesurées des logements performants neufs et renovés: Résultats de la banque de données "BECA"

Nous résumons les résultats de la banque de données "BECA" du LBL, sur la consommation énergétique mésurée de centaines de logements neufs et rénovés. Nous discutons ensuite les rapports multiples entre les caractéristiques physiques et énergétiques du bâtiment et l'effet du comportement. Il faut qu'on cherche une connaissance à la fois plus profonde et plus empirique de ces deux aspects, afin de mieux expliquer d'une part l'écart entre les consommations différentes des bâtiments qui paraissent "similaires" au niveau physique, et de l'autre part l'écart entre la consommation théorique et les résultats mesurés. En général, on réussit mal à séparer les facteurs physiques de l'effet du comportement--même en théorie. Quant au problème du comportement lui-même, il s'agit non seulement d'un manque de données suffisament détailées, mais aussi de la nécessité de mieux définir les conséquences de la consommation énergétique dans l'habitat: c'est-à-dire, l'amélioration du confort et du bien-être des occupants. De ce point de vue, les économies d'énergie ne consistent pas en une simple baisse de consommation, mais en une amélioration du rapport entre la consommation et les services rendus à l'occupant. Enfin, nous discutons plusieurs conséquences de ces perspectives autant pour la recherche que pour la politique énergétique et les programmes.

INTRODUCTION

The Buildings Energy Data Group at Lawrence Berkeley Laboratory (LBL) compiles, analyzes, and publishes a public access data base on the measured energy performance and cost-effectiveness of energy-saving measures in new and retrofitted, occupied buildings. Over the past three years, the "BECA" (Buildings Energy-Use Compilation and Analysis) data base has accumulated measured data on over 2000 energy-efficient buildings (or multi-building projects), mostly in the U.S. and Canada. A near-term objective is to add more data points on energy-efficient buildings in Europe and elsewhere. Objectives of the BECA program are: (a) to document progress in energy-efficient design, construction, and operating practices; (b) to provide empirical feedback to designers, energy management professionals, policy-makers, and conservation program managers; and (c) to identify major areas of remaining untapped conservation potential, as well as gaps in knowledge requiring further research and field monitoring.

Rather than summarizing results from the entire BECA data base, this paper concentrates on the residential sector. BECA-A, New Residences, contains data on over 300 (mostly single-family) buildings designed with energy-saving features. BECA-B (Residential Retrofits) includes data from more than 100 small and large retrofit projects. A third residential data set, BECA-V (Validation), deals with comparisons between predicted and measured building energy performance.[1]

What is the relevance of a data base on measured building energy performance to issues of consumer behavior and energy? First, the BECA data make it clear that physical measurements and engineering analysis, while adequate for unoccupied test structures, are limited in their ability to predict or explain energy performance and retrofit savings in occupied houses. Most studies show large unexplained variance in energy use among physically similar buildings, or else perplexing differences between measured data and performance predictions (based on "average" operating conditions). Accuracy is improved somewhat by more detailed (and expensive) measurements, but to be of value these measurements need to be chosen and performed with great care, so that they accurately reflect occupant behavior, building operation and maintenance, and room-to-room variations, not just simplified, fixed parameters for the building as a whole.

In contrast, early studies of energy-related attitudes and occupant behavior often ignored the complexities of the physical setting, in place of measurements relying on occupant descriptions of the house and self-reports of energy-saving actions--both of which may contain inaccuracies and biases.[2] Ideally, physical and behavioral studies should be seen as complementary, not separate or competing. Pursued in concert, each provides a broader frame of reference for the other, and helps to define further research.[3]

In the following pages, we summarize results from the residential components of the BECA data base, focusing on the variations in energy performance[4] among physically "similar" buildings, as well as on differences between predictions and measurements. We consider the extent to which this variance reflects occupant behavior, among other factors. Finally, we discuss some implications of this variance--widely observed but still poorly explained--both for conservation programs and for future research on buildings and their occupants.

BECA DATA ON MEASURED RESIDENTIAL ENERGY PERFORMANCE

New Houses (BECA-A)

For purposes of comparison, houses in the BECA-A data base are classed in four broad categories: superinsulated, solar active and passive, earth-sheltered, and double-envelope. Increasingly, however, these conventional categories are becoming less relevant, as well-designed new houses attempt to blend two or more strategies.

The sources of BECA data are diverse; both their quality and level of detail vary (within defined limits). In many cases we have been able to supplement monthly energy billing records (a minimum requirement) with more frequent on-site measurements such as sub-metered energy data by end-use, measured indoor temperatures, monitored internal and solar gains, and on-site weather records.

Indicators of space heating performance for BECA-A include: (a) the building's balance temperature, (b) the overall heat loss rate (change in space heat loads with respect to outdoor temperature), and (c) space heat energy use normalized to a "typical" local heating season. These performance indicators, estimated by a regression on monthly (or other periodic) data for each house, are normalized for differences in outside weather and in behavior-driven variables like average indoor temperatures, the amount of closed-off (unheated) space, and "free heat" gains from appliances and occupants (for calculation details see Busch, et al.). Data limitations preclude, however, a quantitative adjustment for other important behavioral variables, such as window openings and use of ventilation fans, which affect infiltration rates, or the use of drapes or shading devices to control solar gains.

It is especially important in energy-efficient houses to normalize measured space heating energy use for differences in internal heat gains and inside temperature settings. Figures 1A and 1B show frequency distributions, prior to normalization, for these two important behavioral variables. In a number of cases, total internal gains from appliance and water heating energy exceed the energy supplied by the "official" heating system. Just the <u>differences</u> among households in behavior-related appliance and hot water use can change space heat energy use by 10 to 20 %. Likewise, for houses with insulation levels typical of BECA-A, a difference of only 1° C in the average indoor winter temperature settings can affect space heating energy by 10 % or more. Yet about one-third of the BECA-A houses have average internal temperatures (prior to normalization) at least 2° C above or below the norm (20° C).

Even after normalizing for weather, inside temperature, and internal gains the BECA-A data for space heating energy use still show significant variation (Figure 1C). By itself, this is not surprising, given the differences in design strategies and construction techniques. Of perhaps more interest is a recent analysis by Fagerson,[5] comparing energy requirements for 16 small sets of <u>physically identical</u>, energy-efficient houses in Minnesota (46 in all) that are also part of the BECA-A sample. Variations in heating energy requirements <u>within</u> each subgroup, typically between 10 and 20 %, were presumably due in large part to occupant effects. Fagerson performed a regression analysis using several rather general physical and occupancy variables (internal gains, reported temperature settings, hours of occupancy, etc.) and found that only about one-third of the variance in energy use could be explained statistically. Although there was some discrepancy between occupant-reported inside temperatures and the temperatures measured (in selected houses), reported temperatures were still the single most significant explanatory variable, accounting for about 20 % of variance.

Retrofitted Houses (BECA-B)

BECA-B contains 115 data points, ranging from single retrofitted houses to program- wide averages for several hundred or several thousand houses. In all, some 60,000 dwellings are represented. Most retrofits involve space heating; a few deal with water heating. Savings are calculated by comparing weather-adjusted energy use for at least a year before and a year after retrofit. Generally, the heating energy data are combined with other ("baseline") uses of the same fuel. This baseline is then estimated as the constant term of a linear regression of monthly energy use data against local heating degree-days.

The results, even after controlling for pre-retrofit energy intensity, building type (single- vs. multi-family), and climate, still show a substantial variation in energy savings for investments of the same magnitude. Much of this variance persists even for subsamples of similar houses which installed the same type of measures, as shown in Figure 2. In general, the range of savings for the middle two quartiles of a subsample can be up to 70 % of the median.

Clearly, not all of this variance is due to changes in occupant behavior--some has to do with physical differences among houses prior to retrofit, differences in the detailed characteristics of retrofit measures (the effective R-value of added insulation, for example), variations in product and installation quality, and measurement error (e.g., inaccuracies in the regression estimates of space heat as a fraction of total energy use). But certainly part is due to pre-/post-retrofit changes in occupant behavior involving temperature settings, number of rooms heated, and internal gains. The percentage variance in energy savings tends to be greatest in mild climates, again indicating a strong behavioral component.

Separating out effects of changed occupant behavior from other variables requires more detailed pre- and post-retrofit building monitoring than has typically been attempted, combined with on-site inspections and occupant interviews. LBL and other National Laboratories in the U.S. are now initiating such a field monitoring program, sponsored by the U.S. Department of Energy; the Swedish Technical University in Stockholm has a similar field research project underway.

Predicted vs Measured Performance (BECA-V)

The BECA-V compilation includes results of over two dozen studies that compare building energy simulations with empirical measurements (about 100 such comparisons). There are notable differences among these studies in the level of sophistication of the models, data quality and detail, and the time-scale of the analyses. In general, the comparisons shed less light on the intrinsic (physical) validity of a model's algorithms than on the importance of the analyst's skill in using the model and interpreting results, the appropriateness of "default" values, and sometimes the accuracy of the so-called "real" (measured) data.

A recurrent theme in BECA-V is that building occupancy greatly complicates the simulation task. Simulation modeling of unoccupied buildings is in general far easier and more accurate--but also less interesting for most purposes (other than the initial validation of a model's algorithms). The BECA-V data show that an occupied building requires more elaborate monitoring to achieve a given level of accuracy with respect to the simulation results. Another interesting finding is shown in Figure 3: the effect, in occupied houses, of varying the time-period of analysis. The distribution of differences between predicted and measured values decreases significantly in going from hourly to daily measurements, suggesting that hour-to-hour fluctuations, whether behavioral or physically-driven, often cancel out in the course of a day.

FACTORS RELATED TO VARIANCE IN ENERGY PERFORMANCE

Variance in the performance of physically similar houses that we observe in the BECA data base is consistent with a number of other occupant behavior studies (not necessarily limited to energy-efficient new houses or retrofits). It is common to find differences of a factor of two in energy use among identical occupied houses.[6] Two recent studies noted even higher occupant-related differences, on the order of 10:1 among elderly residents of attached dwellings,[7] and 20:1 among tenants in one apartment building (located in California's mild heating climate).[8]

It is not clear whether occupant-related variations should be larger or smaller among energy-efficient houses than among conventional ones. In general, one might expect low-energy dwellings to exhibit smaller absolute and larger percentage differences, but in reality the divergence between prediction and measurement may depend more on the building's specific energy-saving features: for example, less variation among superinsulated houses than among active solar homes.

Where does one begin to look for the factors that help explain the variation in energy use among seemingly identical houses? One temptation is to define the search in terms of two obvious categories: (1) previously unnoticed physical differences, such as variations in product quality, unnoticed air leakage sites, localized micro-climates within the same general climate region, etc.; and (2) strictly behavioral ones: thermostat settings, number and length of showers, use of wood stoves, etc.

In fact, the dividing line between physical and behavioral variables is seldom clear-cut; many of the interesting cases involve both. For example, the thermostat-setting behavior of occupants in one apartment unit can have a substantial physical effect on the heating (or cooling) requirements of surrounding units.

A second example involves lowering the ambient temperature setting for a domestic hot-water storage tank. Depending on the circumstances, this common practice can represent either a reduction in the occupant's "level-of-service," a genuine "efficiency" measure, or even a net improvement in the services delivered--in addition to savings in standby energy losses. (a) It is an efficiency measure if the water delivered to each point of use in the house is still hot enough, and (after mixing with cold water) sufficient in volume to meet normal demand patterns. (b) Conversely, this conservation measure represents a reduction in the level of service, rather than an improvement in energy efficiency, if there is not enough hot water for showers or dish washing--when overnight guests come, for example. (3) Finally, a reduced standby tank temperature might improve the level of service, as well as save energy, if it results in a lower maximum temperature at the hot-water tap, one that is safer for small children.

There are other examples of physical and occupancy factors that may influence energy performance, each of which illustrates the interrelatedness of these two categories.

First, with regard to space heating, a great deal of what is often called "occupant behavior" may in fact be due to unmeasured (or inadequately measured) physical factors related to thermal comfort. For example, air temperatures in many houses (especially those with large solar gains or little thermal mass) can vary significantly from one room to another; these variations may themselves change by the hour and season. Large areas of glass, poorly insulated walls, or sites of outside air leakage can introduce radiant exchanges and drafts that reduce comfort--in turn leading to higher thermostat settings or to the displacement of sedentary activities to another room. Of course, the opposite effect also occurs: where household activities naturally concentrate near a fireplace, wood stove, or kitchen oven occupants may lower the air temperature setting to compensate for local radiant gains.

Although, in theory, these factors are susceptible to more precise physical measurement, in practice such monitoring may be difficult, involving not only greater expense but also an increased risk of influencing occupant behavior by more intrusive monitoring.

These "behavioral/physical" effects may also accompany certain retrofits, such as wall insulation, thermal treatment of windows, and sealing of infiltration leaks. Improved comfort may allow (or stimulate) lower air temperature settings, and thus increased savings. It should be noted that a counter-effect has long been suspected--but not yet adequately documented--in the case of envelope retrofits of low-income housing. Where energy savings (measured by changes in energy use) are lower than predicted, this is often presumed to mask an increase in comfort levels and in the number of rooms heated, since both become less expensive after retrofit. To what extent is each hypothesis true; are savings increased by lower air temperatures or decreased by "reinvesting" them in improved comfort and liveable space? Part of the answer lies in more attentive pre-/post-retrofit monitoring, but in part the issue is one of better defining what we mean by "savings."

A further complication: occupant behavior can affect the level of service demanded, as well as the energy efficiency of providing that service. For example, Diamond (op cit.) identifies significant differences among levels of thermal comfort preferred by elderly residents of a California housing project, despite their identical housing units and similar daily activities. Such differences may be physiologically based.

By contrast, a comparative study by Erickson[9] of energy use in middle-class Swedish and U.S. communities finds cultural factors at work. The Swedish households in her sample tended to raise their already cosy winter thermostat settings even more whenever company came, since a slightly overheated room was commonly considered the sign of a "good host." A similar, culturally-induced behavior was noted in a study involving air-conditioned homes in Davis, California: the thermostat was often moved to a cooler setting when company came in summer.[10]

Another important set of effects involves the behavior of institutions, rather than individuals. An example for multi-family buildings is the common practice of the custodian or building operator starting and ending "the heating season" on fixed dates, or alternatively, based on triggering events such as the "first cold spell" in fall or the "first three warm days"in spring. After those dates or events, the system may not be turned back off (or on) in response to changes in the weather. The result may be measurable anomalies (i.e., "occupant effects") in the monthly energy use records, when these are normalized according to degree-days.

IMPLICATIONS FOR ENERGY CONSERVATION PROGRAMS AND BUILDINGS RESEARCH

The preceding discussion suggests at least the broad outlines of two quite different approaches--philosophies, really--affecting both the design of conservation programs and the choice of technologies. One involves the pursuit of energy efficiency in ways that are as "behavior-proof" as possible. The other attempts to use behavior to enhance energy efficiency, either by reducing energy use and/or increasing the resultant level of service.

The first path favors technologies whose performance depends as little as possible on the behavior of building operators or occupants. Thus, shell insulation and replacement of boilers or burners would be preferred to building controls, and more elaborate automated controls chosen in place of simpler manual or semi-automatic ones that might do the same job. Of course, in practice no conservation measure is completely independent of behavior. As noted above, even insulation, when it affects thermal comfort, can lead to lower (or higher) thermostat settings. Moreover, even the most sophisticated computer controls for large buildings require some human intervention for regular checking and calibration. Such human involvement may not always occur, but that is itself an example of behavior that affects building performance.

The philosophy of minimal reliance on "appropriate" behavior by occupants and building operators can also lead to "conservative" program strategies: financial incentives or energy-efficient building codes which assume occupant indifference or even "perverse" behavior. For example, incentive programs may favor tangible hardware improvements over improved operating practices. Compliance with building codes and tax-credit eligibility will be easier for fixed features like multiple-glazing than for occupant-dependent ones like moveable insulated shutters, even if the latter--when properly used--might offer higher R-values, better daytime solar gains, and lower first-costs.

A contrasting design strategy for both buildings and programs attempts to take advantage of behavior where possible, designing buildings in ways that encourage both the occupants and operators to understand and correctly use the energy-saving features. This opens up new possibilities for cost-effective energy management, but will not often succeed without special efforts, for example: careful architectural programming, close attention to design detail, thorough orientation of building occupants and training of operating personnel, and provisions for initial "debugging" and periodic contacts to reinforce the intended behavior. Nor is an "occupant-oriênted" strategy necessarily appropriate in all situations. Occupants as well as building operators differ greatly in their ability, interest, and time available to tend to energy-using systems. Ideally, such diversity should be reflected in incentive programs and building codes. In practice this is rare; multiple options and flexible criteria make programs or regulations more complicated to design and more expensive to administer.

Also consistent with this second view is the design of energy conservation incentives that base payments on <u>results</u> (savings, efficiency improvements) rather than on <u>expenditures</u>. Basing incentives on energy saved is an appealing principle, and makes it possible for relatively inexpensive operating strategies to compete more fairly with hardware improvements. But again, it raises complicated questions of how to properly account for "real" savings, rather than changes in energy use related to weather, comfort conditions, or (for non-residential buildings) operating hours. There is also the question of how to assure that the improved energy management practices remain in effect after the initial period. Of course, this same concern should be raised for energy-saving hardware that requires--but does not always receive--periodic mainenance and adjustment.

For the sake of clarifying these two approaches we have also cartooned them somewhat; clearly both have some value but either can be misapplied if carried to an extreme. Still, the most common tendency for both conservation programs and building designs has been a bias toward the first path: "behavior-proof" conservation. Some shift in emphasis toward the second seems warranted. In turn, this will require timely input from new types of research that can blend the methods (and insights) of the behavioral and engineering sciences.

Moving to research issues, then, we find a widespread need for more detailed field research, combining physical measurements with behavioral analyses. The complexity and cost of such studies also means that they must be carefully planned, designed to test well-defined theories, built upon relevant prior work, and applied to a sample that eventually can be generalized to large segments of the building stock. In short, they must follow more closely the classic scientific tradition, one that has been in some cases sidestepped by early, more exploratory (or simply more haphazard) investigations.

The scope for such studies also needs to be broadened beyond space heating in single-family residences. Also of interest are combined physical/behavioral field studies of: residential water heating (see Kempton and Weihl, op. cit.); air conditioning use in warm climates;[11] interactions of tenants and building operators in large multi-family structures; and similar individual and institutional behavior issues within the extremely diverse non-residential sector.

We suggested earlier that the links between physical and behavioral factors may be tied to a further issue: the relatively primitive nature of indicators for the "output" of energy use in buildings. Energy efficiency, properly defined, is <u>not</u> just reduced consumption, but an improvement in the relation between energy inputs and the quantity and quality of services provided to occupants: thermal comfort, aesthetics, privacy, etc. In the case of residential space heating, for example, both logical consistency and the explanatory power of the data could often be improved by moving beyond the current output indicator, typically the floor area (or volume) of living space heated to a specified average air temperature. A more complete output indicator might represent thermal comfort (air temperature, humidity, air movement, radiant exchanges), as a function that varies according to time, location within the house, and the activities, clothing, and comfort preferences of the occupants.

Finally, the development of a more complete set of "output indicators" for building performance needs to address energy-related factors other than efficiency, for example, building responsiveness and controllability. For some occupants these characteristics may be at least as important as aesthetics, reliability, or maintenance costs. Yet, current indices of building performance within the BECA data bases, for example, fail to allow at all for the value of controllability. The refinement of concepts, definitions, and analytical techniques thus needs to advance in parallel with better data.

CONCLUSION

Two general conclusions may be drawn from the preceding discussion. First, it is both important and difficult to better integrate the "engineering" and "behavioral" perspectives on building energy performance. Purely behavioral studies or attitude surveys can be misleading without the physical context provided by building measurements. Conversely, behavior is an important (if perhaps not conclusive) factor in explaining the variance in energy performance, both across buildings and between measurements and predictions.

Yet research that genuinely bridges these two perspectives is rare, not only because it is more difficult and expensive, but because it may appear threatening to both the behavioral and physical science "cultures," as well as to their traditionally separate funding sources.

A final observation: the approach used by the BECA data base to systematically compile, critically review, and publish comparative data on measured physical performance of buildings may also be useful to apply to data from behavioral research. In fact, a common approach to data compilation and analysis may represent a first step towards bridging the two perspectives. In its own data compilations, the Buildings Energy Data Group at LBL is attempting to better understand the sources of variance among buildings, and between predictions and measurements. This will lead us to seek out and incorporate better data and new insights on both physical features and occupant behavior. Data contributions or suggestions from readers are always appreciated.

ACKNOWLEDGMENT

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NOTES

1 For detailed BECA results, see the following LBL Reports (also presented at the 1984 ACEEE Santa Cruz Summer Study on Energy Efficiency in Buildings, August 1984, American Council for an Energy-Efficient Economy, Washington, DC): J. Busch et al., "Measured Heating Performance of New, Low-Energy Homes: Updated Results from the BECA-A Database," LBL-17883, May 1984; C. Goldman, "Measured Energy Savings from Residential Retrofits: Results from the BECA-B Project," LBL-17885, May 1984; and B. Wagner, "Verification of Building Energy Use Models: A Compilation and Review," LBL-17884, May 1984. There are also significant behavior-driven variations in energy performance among non-residential buildings in other BECA sub-elements, but these are beyond the scope of the present paper.

2 Differences between self-reported and measured thermostat settings, as well as an exemplary pioneering effort to combine physical measurements and behavioral research, are discussed in W. Kempton and S. Krabacher, "Thermostat Management: Intensive Interviewing Used to Interpret Instrumentation Data." Kempton and his colleagues at Michigan State University, USA, have applied similar techniques to a detailed examination of water heating energy use behavior, in W. Kempton, "Residential Hot Water: A Behaviorally-Driven System," and J. Weihl, "Family Schedules and Energy Consumption Behaviors." All three papers were presented at the 1984 ACEEE Summer Study.

3 For an extended discussion of behavioral research perspectives on energy use, based on a recent National Academy of Sciences study, see P.C. Stern and E. Aronson (eds), Energy Use: The Human Dimension, N.Y., W.H. Freeman Co., 1984.

4 BECA data on economic cost-effectiveness also shows significant variation on the cost side--some of it probably behaviorally driven (purchase preferences, maintenance practices, etc.). That interesting topic must await a future paper.

5 M. Fagerson, "Statistical Analysis of Lifestyle Factors in Heating Energy Use of New and Weatherized Minnesota Homes," paper presented at the 1984 ACEEE Summer Study.

6 R.C. Sonderegger, "Movers and Stayers: The Resident's Contribution to Variation Across Houses in Energy Consumption for Space Heating," in R. Socolow (ed.), Saving Energy in the Home: Princeton's Experiments at Twin Rivers, Cambridge, Mass., Ballinger, 1978.

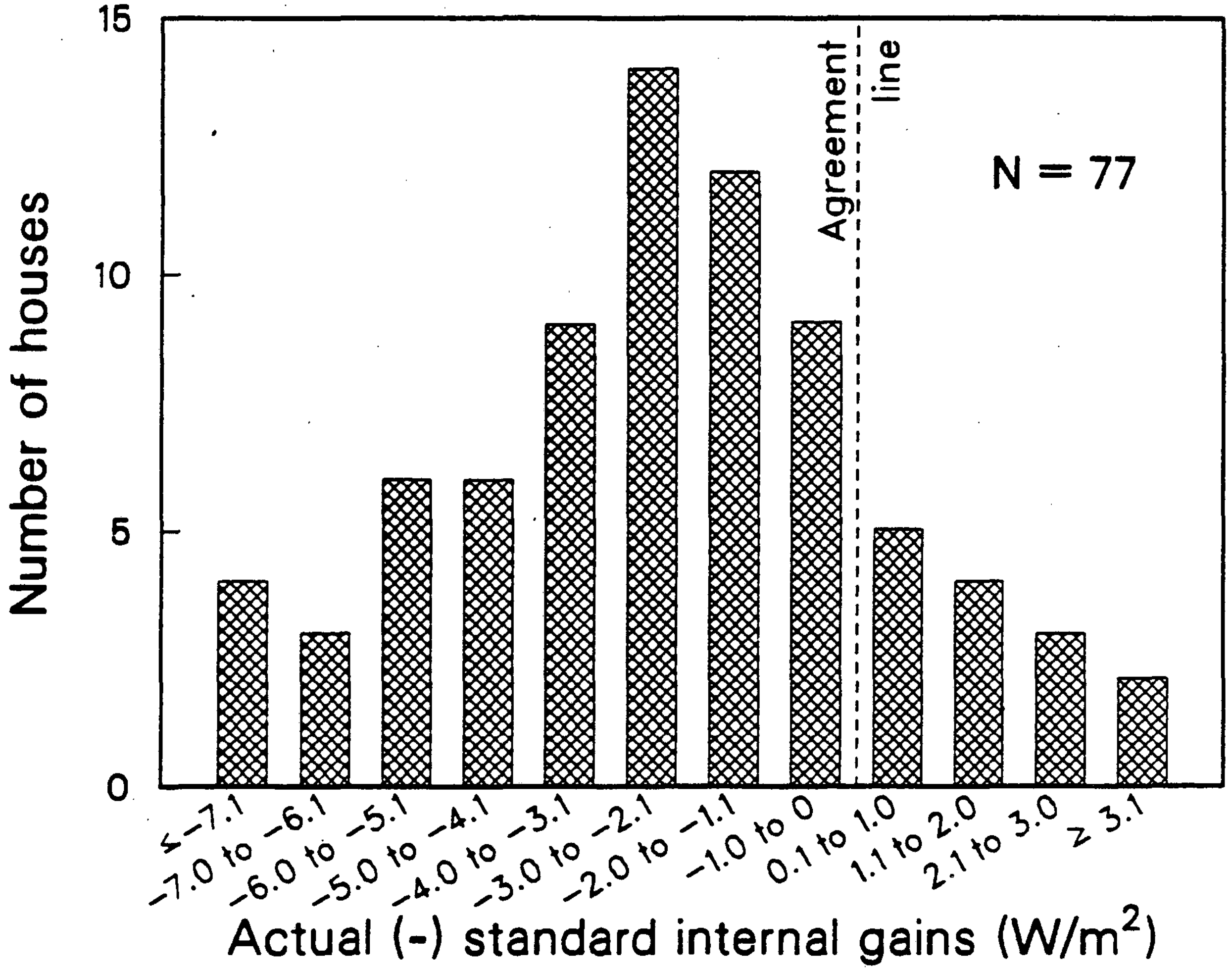
7 R. Diamond, "Energy Use Among the Low-Income Elderly: A Closer Look," paper presented at the 1984 Santa Cruz Summer Study, August 1984, also available as an LBL Report.

8 R. Lipschutz, et al., "Some Technical and Behavioral Aspects of Energy Use in a High-Rise Apartment Building," paper presented at the conference on Families and Energy: Coping with Uncertainty, Michigan State University, 1983.

9 R. Erickson, "Household Energy Use in Sweden and Minnesota: Individual Behavior in a Cultural Context," presented at the 1984 Santa Cruz Summer Study.

10 B. Hackett, et al., "Comparing the Methodologies of Research on Household Energy Consumption," in J. Harris and C. Blumstein (eds.), *What Works: Documenting Energy Use in Buildings*, based on the 1982 Santa Cruz Summer Study, ACEEE, Washington D.C., 1984.

11 E. Vine, et al., "The Application of Energy Models to Occupied Houses: Summer Electricity Use in Davis," *Energy* 7(11): 909-925 (1982).



XBL 858-3319

Figure 1A. Frequency distribution of differences between measured (or estimated) actual internal gains and standard internal gains, per square meter of heated floor area, for new energy-efficient houses in the BECA-A data base. Standard gains are calculated using the formula I_s (W) = 706 + 3.24 x area (m^2). Source: Busch, et al.

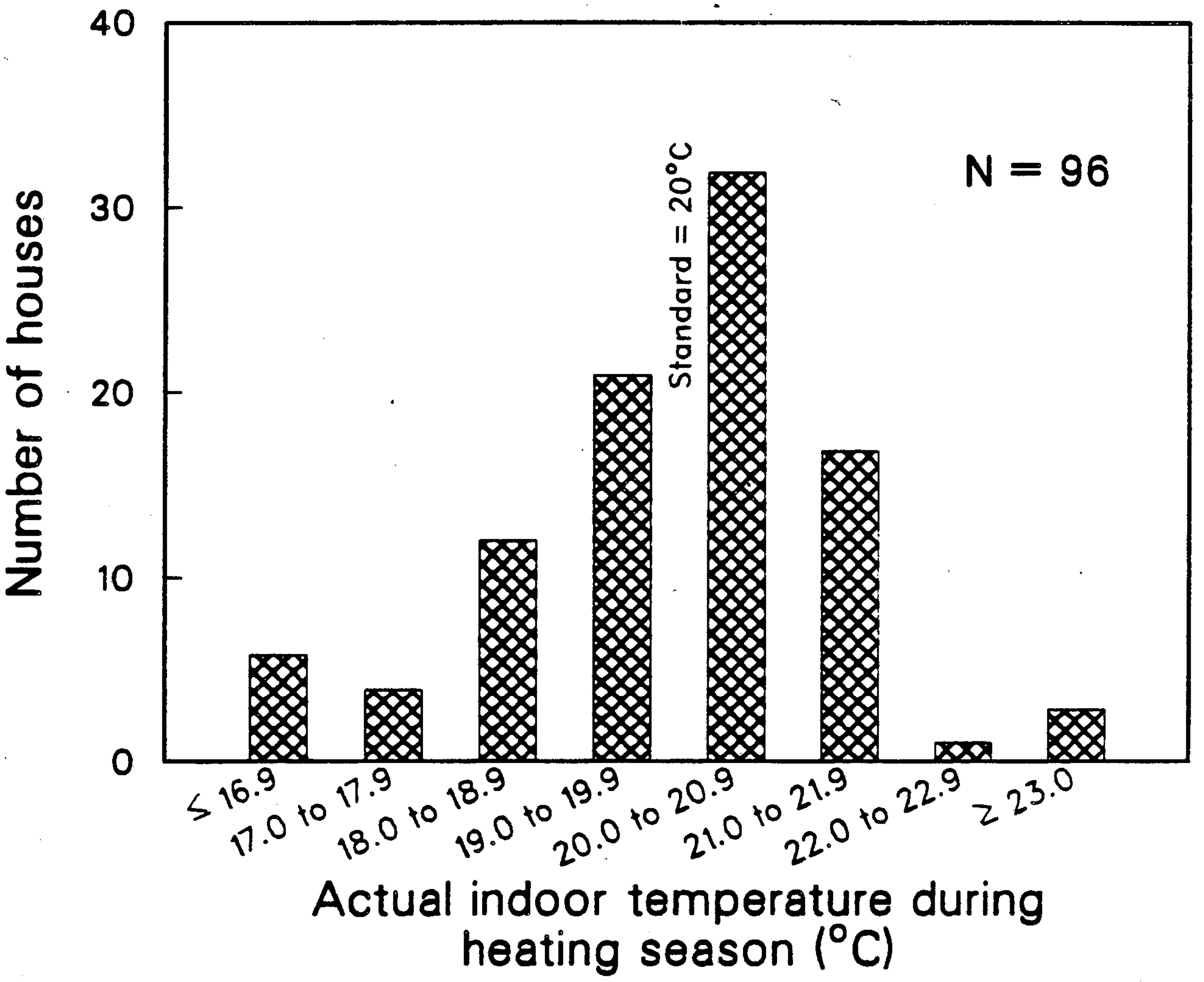


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Figure 1B. Frequency distribution of measured average indoor temperatures during the heating season, for BECA-A houses. The standard indoor temperature is chosen as 20°C, close to the median for this sample. Source: Busch, et al.

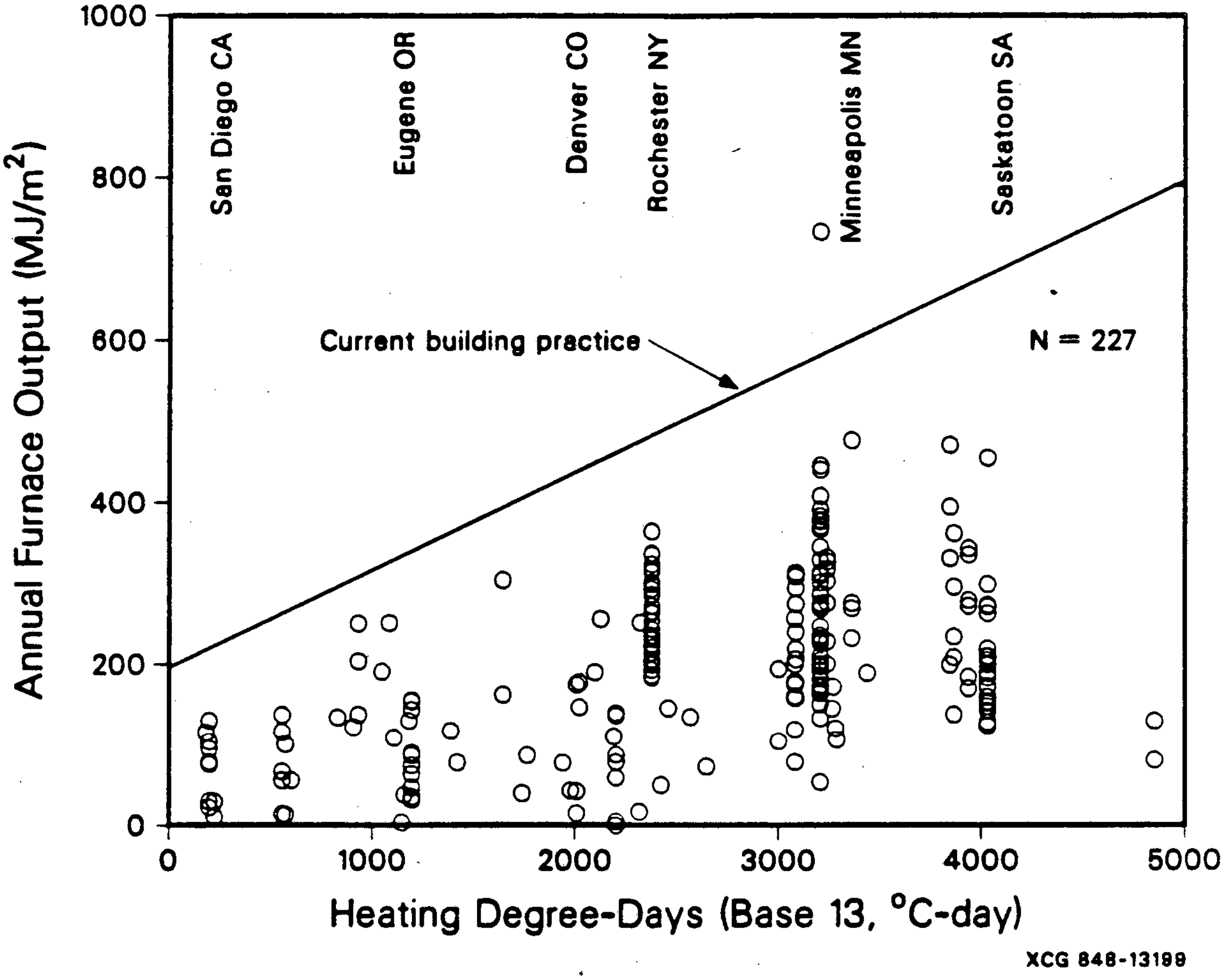
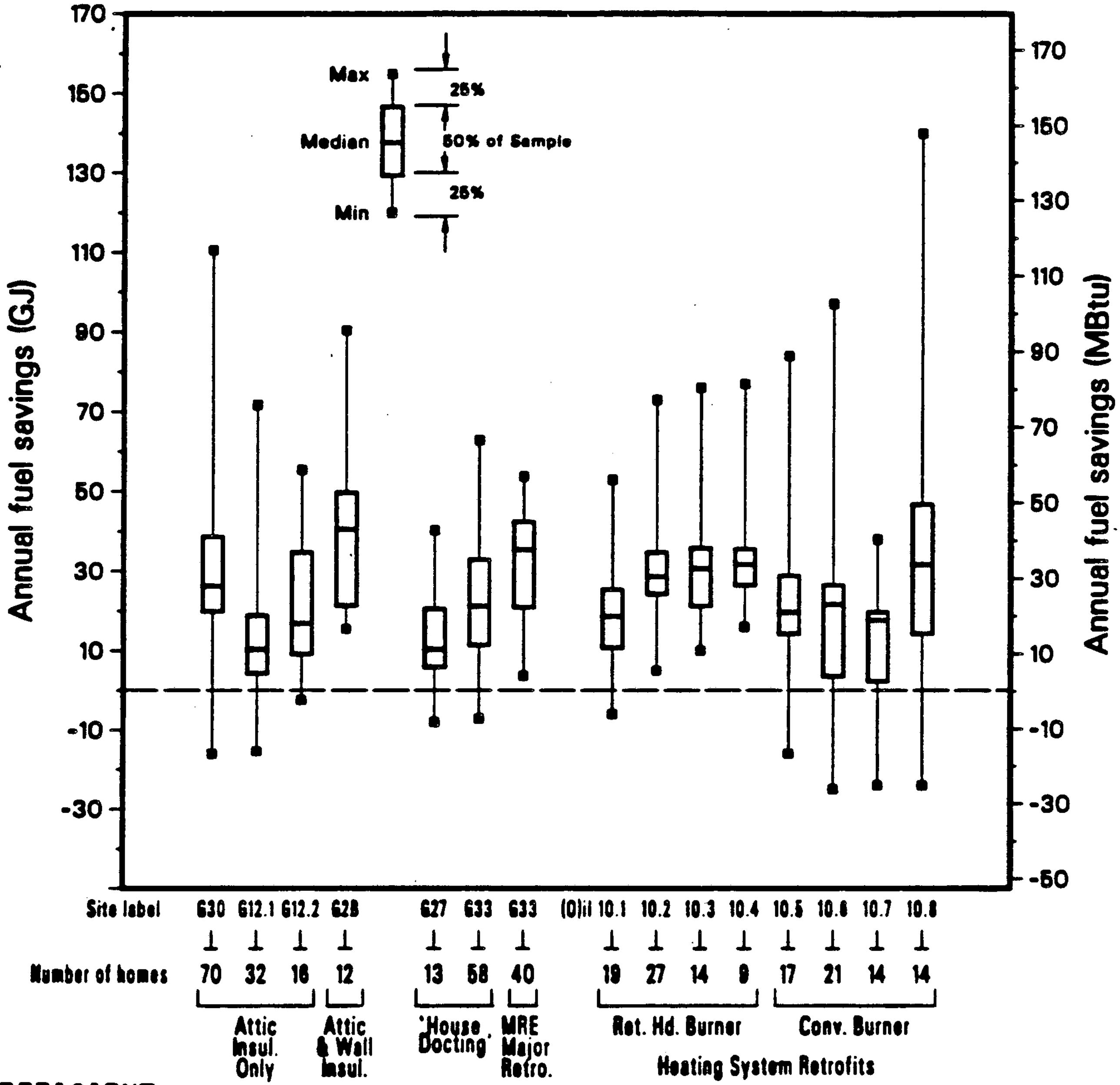


Figure 1C. Annual furnace output (normalized for interior temperatures and internal gains) vs. heating degree-days (base 13° C) for low-energy houses in BECA-A. The solid line approximates "typical building practice" for new U.S. houses in the early 1980's. In some cases, similar or identical houses in the same climate have significantly different heating energy requirements, even after normalizing for inside temperatures and internal gains. Source: Busch, et al.



COEFFICIENT OF VARIATION 0.6 1.0 0.51 1.10

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Figure 2. Range of annual, weather-normalized fuel savings among households installing similar retrofit measures, from the BECA-B data base. Weather-adjusted consumption increased, rather than decreased, in 5 % of the households. Source: Goldman

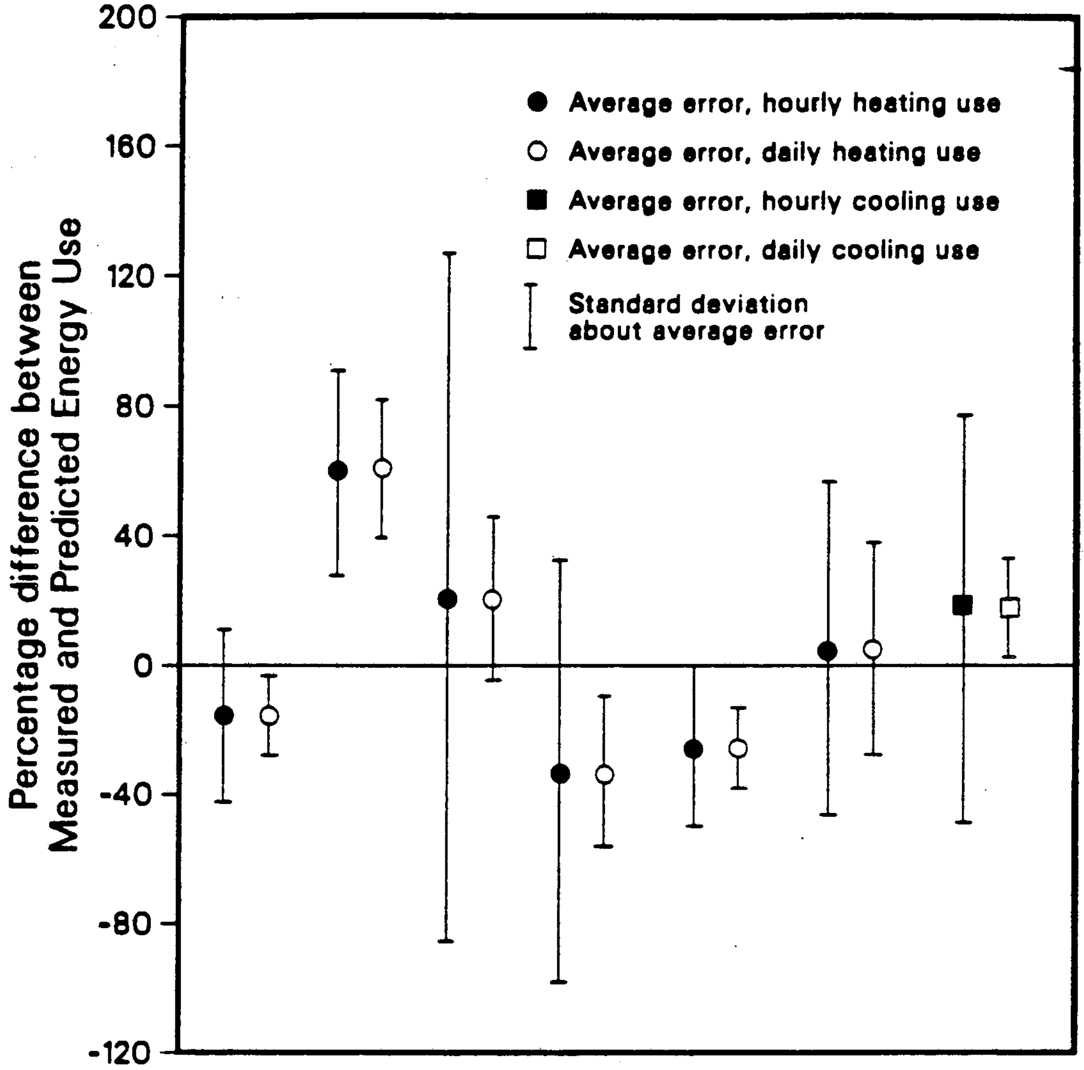

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Figure 3. Percentage difference between predicted and measured daily and hourly energy use for residential heating or cooling, from the BECA-V data base. Daily and hourly values are shown for each house. The points are averages; the bars show standard deviations. The variances suggest that both behavior (temperature settings, appliance use) and physical parameters (thermal lag, system cycling) are more difficult to predict on an hourly basis; over a day they tend to average out. Source: Wagner