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VALIDATION OF BUILDING ENERGY ANALYSIS TECHNIQUES
A SUMMARY REPORT OF BUILDING ENERGY COMPILATION AND ANALYSIS - PART V (BECA-Val)

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ABSTRACT

BECA-V compiles and reviews comparisons of building energy analysis techniques to measured building energy use. This paper summarizes preliminary results for the 12 studies reviewed to date. For commercial buildings, detailed computer programs were accurate to within about 10% when correct input data were available. For residential buildings, accuracy of building energy analysis programs was generally better than 10% when the buildings analyzed were intensively instrumented and monitored to eliminate errors in input. Two simplified programs suitable as building energy efficiency rating tools were, on average, accurate to within 15% for submetered and for less intensively monitored occupied houses. We plan to expand this preliminary compilation, and invite contributions to the review.

1. INTRODUCTION

1.1 Background

Spurred by the fuel shocks of the 1970s, development of building energy analysis techniques accelerated rapidly, producing, by 1982, several generations of detailed computer programs designed to predict residential and commercial building energy use[1,2] (see Fig. 1 for a partial genealogy). At the same time, a great variety of simplified analysis techniques, some hand calculator-based, some consisting of no more than a checklist or point scoresheet, were developed by users who could not afford the time and/or expense required to run the detailed programs. Pacific Northwest Laboratory has compiled a partial catalog of energy analysis tools now in use in the U.S., numbering 47 as of May 1982;[3] others are described in, e.g., references 1 and 2. Both detailed and simplified analysis tools currently fill a variety of functions: as engineering design tools for new construction; in audits and retrofit recommendations; in calculating national or regional energy trends and scope for conservation; in determining compliance with building energy standards; in sizing HVAC equipment; in testing eligibility for participation in conservation incentive programs; and as a basis for energy efficiency comparisons between houses.

The usefulness of any analysis technique depends on a number of criteria, including ease of use, flexibility, and cost. It also depends fundamentally on the accuracy of the technique, i.e. how closely predicted building energy use matches measured consumption of a real building, under specified conditions. Published comparisons between predicted and actual energy consumption are relatively few, probably due to the difficulty and expense of performing careful monitoring, data collection, data preparation, and evaluation of results, particularly for occupied houses. Nevertheless, a good understanding of the capabilities and limitations of an energy analysis technique is critical to using it properly in any of the applications listed above. Although we will focus discussion in this paper on development of energy rating systems, our continuing compilation and review of comparisons between energy analysis predictions and measured energy use is intended to assist the users of analysis techniques in a variety of applications.

1.1 Energy Ratings

In calculating building energy consumption for a rating, the accuracy of the output of course depends on the accuracy of the following four inputs and algorithms:

1. Weather,
2. Operational description: schedules for thermostats, appliances, window management, and venting,
3. Physical description: U-values, dimensions, infiltration, etc.,
4. Algorithms used in energy analysis, and microclimate corrections to remote weather data to obtain on-site weather information.

In order to make meaningful comparisons among houses, items 1 and 2 can be standardized -- i.e., all programs can be run on standard reference weather, and assumed to have standard schedules and occupancies. The remaining sources of error are then INPUT DATA, and ALGORITHMS. This suggests a two-step process to validate the accuracy of a rating system:

1. Validation of the program algorithms, by expert program users, inputting carefully measured building data and known or simulated occupancy and weather. Occupancy and weather used in validation of algorithms should be in a range which includes the standard weather and operating conditions hypothesized above.

2. Certification of users, by testing the professional auditor or rater's ability to provide the correct inputs.

This paper will focus primarily on the first step. We review studies of the ability of energy analysis programs, given correct occupancy, weather, and construction data, to predict measured energy consumption. In practice, errors in input are not always easily detected, even under research conditions. However, we indicate the source and quality of the input for the studies cited, and point out examples in which known input errors affected energy use predictions.

We divide the remainder of the paper into three parts: some brief examples of validation of commercial building analysis; a review of residential building program validations; and conclusions. Studies in the residential building section are divided according to the detail of input data and degree to which effects due to occupancy were controlled or monitored. Such a categorization helps to indicate whether a given comparison was likely to reflect errors from sources other than program algorithms (i.e. measurement of weather, occupant schedules, or building characteristics).

2. COMMERCIAL BUILDINGS

Commercial building energy analysis presents an obvious application of computer programs, because the complexity and expense of the building and heating, ventilating, and air-conditioning (HVAC) systems often require engineering analysis, and because increasing energy costs increase the attractiveness of investment in more efficient systems. Presumably, then, there has been for some time a strong incentive to develop accurate analysis programs for commercial buildings, and experience in their use to date may provide some insights and lessons for users of residential building analysis programs. Figure 1 summarizes results of three studies of predicted vs. measured energy use in commercial buildings.[4-6] The eleven buildings represent a wide variety of building types, locations, and HVAC systems. Detailed audits were available in all cases. In seven cases billing data were available to the program users during the simulation (Diamond et. al.); in two cases billing data availability during simulation is unspecified (Yuill et. al.); and in the remaining two cases (Herron et. al.) the simulations were "blind", i.e. performed without changing inputs after reference to actual billing data, except for correction of two major errors in occupancy data supplied by a subcontractor. Figure 1 shows that the predictions all fell within about 10% of the measured use.

3. RESIDENTIAL BUILDINGS

3.1 Comparisons in Instrumented Buildings, Unoccupied and Monitored Occupancy

An early program with both the capability to model residential buildings and extensive experimental verification of algorithms is the National Bureau of Standards Load Determination (NBSLD) program. NBS has undertaken verification of NBSLD in their environmental test chamber using full-scale buildings with known thermal characteristics. The environmental test chamber offers the advantage of precisely controllable temperatures and humidities, which can be set to average sol-air temperatures for the monitored building. Effects of wind, rain, and visible solar gain are excluded. Narrowing the range of weather variables, while it restricts the scope of verification, simplifies comparison of predicted and measured data. Future comparisons under natural weather conditions have been planned.

Peavy et. al.[7] compared predicted vs. measured electric heating in a 20'x20'x10' concrete building inside the test cell (shown by "+"s in Fig. 2). Intensive monitoring provided heat flow and temperature distribution data. Temperatures in the test cell simulated a 24 hour diurnal cycle, which was repeated several times to allow transient heat flow patterns to die out before final measurements were made. Five of the ten test runs (one 24 hour cycle per test run) were made with no heating, in order to see the effect on indoor temperature swings of variations in window and internal mass configurations. In the remaining five runs, a thermostat regulated electric heaters to keep indoor temperature constant. The predicted heating load for one 24 hour cycle averaged 4.6% lower than the measured heating load, with a standard deviation (SD) of 3.4%. In these five tests, the predicted maximum heat flow rates (of interest when sizing HVAC equipment for

buildings) were within 8% of measured rates, while maximum rates predicted by a conventional steady state method ranged from 29% to 69% higher than measured values. Steady state methods did, however, predict total daily heat load to within an average of 7.2% (see Figure 2), with an SD of 3.6%. The discrepancy in predictive accuracy for maximum heating loads is not surprising in the high mass building, since NBSLD takes thermal storage (thermal lag) into consideration, whereas the steady state model does not.

In a second experiment, Peavy et. al. investigated the thermal performance of a four-bedroom, wood-frame townhouse.[8] Temperature cycles simulated recorded weather conditions for winter, summer, and fall (one day each) in Macon, Georgia and Kalamazoo, Michigan. Both gas and electric furnace systems were tested in seven "winter day" test runs; the eighth run was a "pull-down" test and runs 9 and 10 were "summer" and "fall" day tests, respectively. Lightbulbs and appliances simulated occupancy (including metabolic heat from occupants) by a family of six during five of the tests. For the six tests of interest for simulation on NBSLD, error in predicted 24-hour energy use averaged -0.67%, with an SD of 3.1% (represented by "X"s in Fig. 2).

In conjunction with the development of a detailed building simulation program for the Electric Power Research Institute (EPRI), Sepsy et. al. of the Ohio State University (OSU)[9] instrumented and monitored 57 residences. Data from the most intensively submetered and audited residences (6 single-family dwelling and 3 townhouse apartments, all located in Columbus) were used for modification and verification of the simulation program. Energy consumption predicted by the Residential Energy Analysis Program (REAP) was compared to metered data on an hourly, daily, and total (varying from 7 to 27 days) basis. Three of the houses, operated under a variety of weather and occupancy conditions (including unoccupied) and, in one case, with a variety of heating systems, provided data for a total of ten comparison periods. Average percentage errors for furnace and baseboard heating, weighted by monitoring duration, were under 5%. Predicted heatpump heating was low by 16%, a result attributed by the researchers to inaccurate modeling of defrost cycles. Air conditioning average error was -8.2% (see circles in Fig. 2).

In further validation work on REAP, Talbert et. al. of Battelle, Columbus Laboratories selected for simulation six of the 48 buildings monitored by OSU outside Columbus.[10] Monitored data were less complete than in the OSU study, necessitating engineering assumptions to complete input decks. Missing data ranged from such items as thickness of wall paneling and presence of curtains to critical information, for a few houses, such as indoor temperature and type of air-conditioner. In contrast to the OSU study which was designed to use audit and monitoring data to improve program accuracy, the goal of the Battelle study was to make "blind" assumptions, i.e. with no subsequent revisions of input or algorithms, in order to test the current state of model accuracy.* Of the six heating and four cooling simulations, two cooling simulations were eventually rejected because of critical missing information. Results of the remaining runs are shown in Fig 3 (represented by "+"s and "x"s). Average error was 5.1%, with a SD of 36%. The large SD reflects, in part, one run for which the error was +60%. Weather data for the run were questionable, however, discrepancies were inadequate to explain the total error.

3.2 Comparisons in Submetered, Unmonitored Buildings

Although submetering only the space-conditioning use may be inadequate for detailed verification of complex programs, it can be quite useful, particularly if indoor temperatures are also measured, in overall verification of simple or complex heating/cooling models. Dickinson and Sonderegger compared predictions by Lawrence Berkeley Laboratory's (LBL) Computerized, Instrumented Residential Audit (CIRA) to submetered heating data for 14 electrically heated houses near Hanford, Washington.[11] The houses were divided into 3 cells of 4-5 houses each, according to type of retrofits received. Average heating consumption of each cell for each test year was normalized to 1979 weather and compared to CIRA predictions for an "average" house description of that cell. Average error was -3.1%, with a SD of 6.9% (circles in Fig. 3).

3.3 Comparisons in Uninstrumented, Unmonitored Houses

Comparisons of predicted vs. metered energy use in occupied, uninstrumented houses actually tests the accuracy of input (auditor skill) as well as program accuracy. However, in the following three comparisons, the audit and input were made by researchers, and in the second two comparisons some houses were instrumented and submetered for at least a short time. Further, input requirements for the three programs tested were less complex than for the detailed comparisons discussed elsewhere in this paper. The following comparisons should therefore

*With one exception, a house with nighttime thermostat setback patterns where the simulation was rerun to include the setback.

reflect reasonably small input error.

Wagner[12] analyzed total yearly gas consumption of eight tract houses in Walnut Creek, California, comparing CIRA predictions to utility bills. Because weather files for Walnut Creek was unavailable at that time, she used data from Sacramento. Comparison of average monthly temperatures for the two locations showed agreement to within a few ^{o}C. The houses had been selected from a large sample for another experiment in part because of a good degree-day vs. gas use correlation, which may have biased the results favorably. However, it also quite possible that the houses whose gas use correlated poorly with standard degree days either 1) had heated pools, spas, or hot tubs, which would not have affected CIRA's ability to accurately predict the building energy use; or 2) practiced thermostat setbacks which CIRA can model, but which do not necessarily yield good correlations. Average error in total annual gas use was -0.26%, with a SD of 14% (circles in Fig. 4).

Using a simplified computer program designed for analysis of space heating in residential buildings (HOTCAN), Dumont et. al.[13] analyzed heating consumption of 9 detached houses in Saskatoon. Most of the buildings used substantial passive solar heating (fuel requirements for space heating ranged from 36 to 80 GJ/year) and all but one used air-to-air heat exchangers. Three of the houses were submetered; heating use for the others was estimated by subtracting summer base use and adjusting for number of occupants. Interior temperature estimates were based on one week hygrothermograph measurements. Average error was -1.6%, with an SD of 9.7% ("+"s in Fig. 4).

Most of the studies cited in this paper investigated heating use. Cooling energy use, in general, presents a much more difficult analytical problem, since there are a larger number of important driving forces, temperature differentials are smaller, and use of an air-conditioner often appears more discretionary than furnace use. Comparison to non-submetered utility data by separation of cooling and estimated base appliance load is also difficult. In a study to carry out such an analysis, Vine et. al. of LBL[14] compared total electric and cooling use predicted by DOE-2.1A to metered total electric and estimated cooling use in 74 single family dwellings in Davis, California. Audit data were obtained by utility auditors and verified from city records and discussions with builders, under the constraint that the detail be no greater than that obtainable in a relatively low-cost audit program. Thermographs recorded indoor temperatures in twenty-two houses. Predicted total electricity use for this subset of houses, using thermograph data for inside temperatures, was 26% higher than the measured average. Surprisingly, substituting occupant-reported indoor temperatures in the same group reduced the overprediction to 14%. The prediction for all 74 houses was 18% high (triangles in Fig. 4.). Regression analysis of predicted vs. actual cooling loads (the latter estimated from billing and audit data) yielded an r^2 of only 0.12. The r^2 increased to 0.30 when actual consumption in April was used to estimate electric baseload, rather than audit data. Problems with audit and weather data are cited to explain the degree of error in individual estimates of electric use.

In a sufficiently large sample of houses, variations in occupant effects should average out, so that a prediction of average use may be accurately based on average inputs. Colborne et. al. of the University of Windsor analyzed electric heating use of 75 houses in Windsor, Canada.[15] The houses were all of the same design, built by the same contractor, and in the same subdivision. Indoor temperature, infiltration, and exact internal gain data were unavailable. Standard assumptions were made for all unknown data and were not subsequently changed to improve agreement of predicted and measured consumption. The actual average heating use of the 75 houses was estimated by subtracting the summer baseload from each billing period. DOE-2 simulations of the house with and without basement heating came within 9% of measured use; weighting the simulated results by the percentage of heated and unheated basements (determined by audit) yields an average predicted consumption which is within 3% of the measured average. Given the large number of assumptions and the lack of submetered data it is not possible to tell how much of the agreement is attributable to 1)canceling of errors in inputs and algorithms; 2) cancellation of variations in occupant use; and 3) accuracy of algorithms. A modified degree day calculation using the same input assumptions yields a weighted average error of 9%, which suggests that the DOE-2 algorithms increased the accuracy of calculations compared to degree day analysis (see Fig 4).

4. CONCLUSIONS

Tables 1 through 4 summarize the results from the 12 studies reviewed. Accuracy of energy analysis programs was generally better than 10% for buildings with accurate construction data and carefully monitored or controlled operation. Accuracy of predictions for groups of buildings, as expected, tended to be better than individual predictions. Accuracy tended to decrease as quality of input data decreased, but for buildings with submetered data or reasonably detailed audit data, 2 simplified programs, suitable for audit/rating pro-

grams, predicted heating and total gas consumption of individual buildings within a standard deviation of 10-15% error. These results are encouraging, if the goal of a rating system is in the range of ±15% accuracy in predictions of "standard house" energy consumption. However, we note that:

1. The number of comparisons cited is still small, as is the total building sample size.

2. Comparisons of predicted vs. measured cooling consumption are scarce, and, to date, not encouraging on an individual building basis

3. We know of no experimental results from tests of the accuracy of auditor inputs.

4. Published studies tend to reflect comparisons in which accuracy was relatively good. It would be useful to know when and why computer predictions fail.

This paper is a preliminary version of a more complete review of energy analysis program validations. We invite contributions to our continuing data collection and analysis effort.

6. ACKNOWLEDGEMENT

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

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TABLE 1. Commercial Buildings: Comparisons of Predicted vs. Metered Energy Use

A	B	C	D	E	F	G
Program Name	Ref. #	# of Bldgs	Onsite Weather	Systematic Error %[1]	SD[2] %	Duration of Monitoring, Comments
DOE-2.0A	1	7		-3.4	7.7	1 year. Monthly SD~17%.
BLAST	3	1	Y	+12.1	NA	1 month. Dental clinic. Erroneous occupancy gave -7.2%, but correction improved individual predictions of cooling and appliance use
BLAST	3	1	Y	-5.2	NA	1 month. Battalion HQ, total electric use. Erroneous occupancy gave +49.6%
BLAST	2	1		-13 E -8 S	NA NA	Office building. E= electricity, S= steam
BLAST	2	1		-1 E +0.3 G	NA NA	Office building. E= electricity, G= gas

[1]Systematic error is the average of ((Predicted - Measured)/Measured).

[2]SD= standard deviation of percentage error for several runs or buildings NA= not available or not applicable

TABLE 2. Residential Buildings, Intensively Instrumented and Monitored Predicted vs. Measured Energy Use

A	B	C	D	E	F	G
Program Name	Ref. #	# of Bldgs	Onsite Weather	System Error %[1]	SD[2] %	Duration of Monitoring, Comments
NBSLD	4	1	Y	-4.6	3.4	1 day, 5 simulation runs. Massive house in environmental test cell.
NBSLD	5	1	Y	-0.67	3.1	1 day, 6 simulation runs. Townhouse in environmental test cell.
REAP	6	3	Y	-3.4*		1-4 week. *Time weighted average error.

[1]Systematic error is the average of ((Predicted - Measured)/Measured).

[2]SD= standard deviation of percentage error for several runs or buildings NA= not available or not applicable

TABLE 3. Residential Buildings; Submetered, no Monitoring. Predicted vs. Measured Energy Use

A	B	C	D	E	F	G
Program Name	Ref. #	# of Bldgs	Onsite Weather	Systematic Error %[1]	SD[2] %	Duration of Monitoring, Comments
REAP	7	6		5.1	36	1 week.
CIRA	8	14		-3.1	6.9	1 year. 3 groups of 4-5 houses each.

[1]Systematic error is the average of ((Predicted - Measured)/Measured).

[2]SD= standard deviation of percentage error for several runs or buildings NA= not available or not applicable

TABLE 4. Residential Buildings; No Submeters or Monitoring. Predicted vs. Measured Energy Use

A	B	C	D	E	F	G
Program Name	Ref. #	# of Bldgs	Onsite Weather	Systematic Error %[1]	SD[2] %	Duration of Monitoring, Comments
CIRA	9	8	N	-0.26	14	1 year. Tract houses.
HOTCAN	10	9		- 1.6	9.7	1 year. Detached houses in Saskatoon.
DOE2.1A	11	74	Y	+18	NA	3 months. Total electricity use in detached houses in Davis, CA.
"	"	22	Y	+26	NA	
DOE-2	12	75		3	NA	1 year. Space heating average of identical houses in Windsor.

[1]Systematic error is the average of ((Predicted - Measured)/Measured).

[2]SD= standard deviation of percentage error for several runs or buildings

NA= not available or not applicable

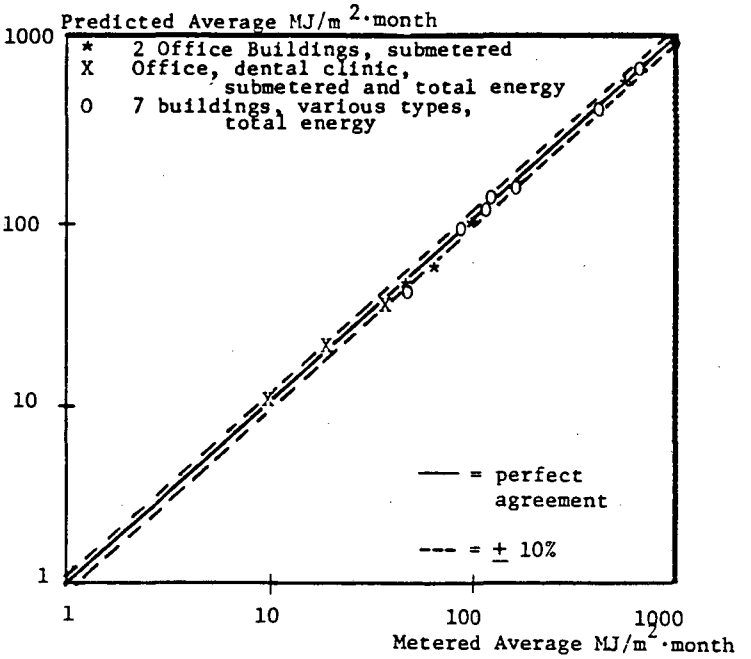
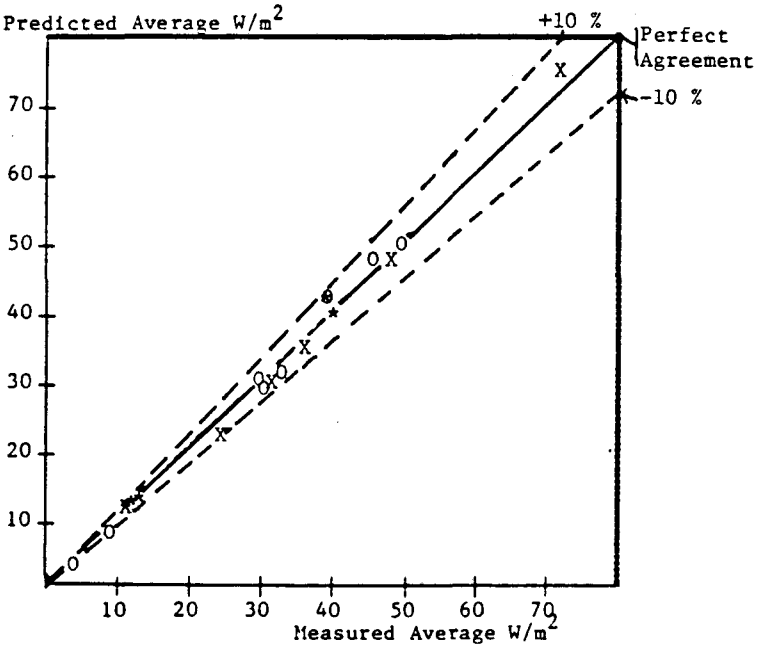


Figure 1 Predicted vs. Metered Site Energy Use in Commercial Buildings. For degree to which analysts had billing information during simulation of buildings, see text.



* NBSLD, high-mass house in test chamber, heating only
X NBSLD, townhouse in test chamber, heating and cooling
0 REAP, detached houses outdoors, heating and cooling

Figure 2 Predicted vs. Metered Site Energy Use in Intensively Monitored Buildings. For degree to which analysts had access to metered data during simulation, see text.

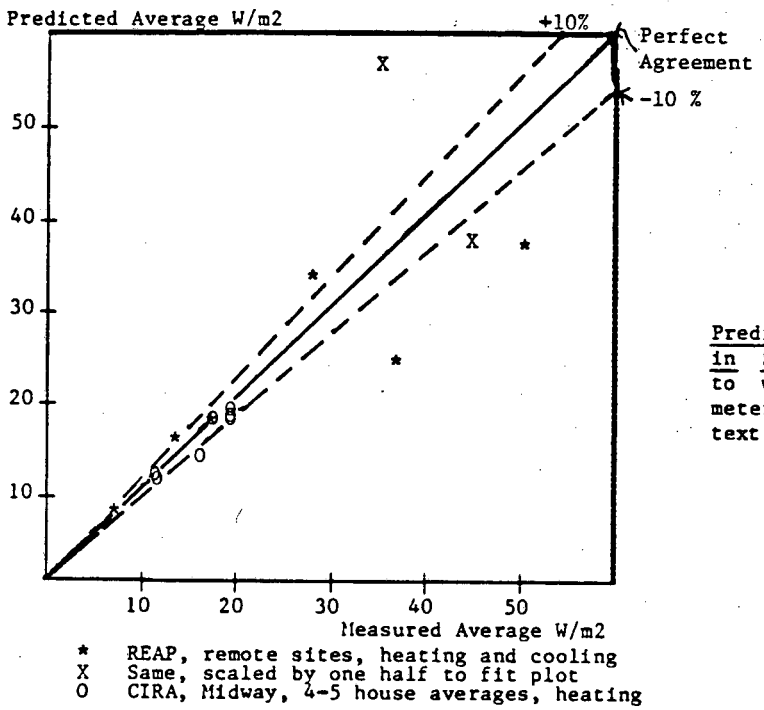


Figure 3

Predicted vs. Metered Site Energy Use in Submetered Buildings. For degree to which analysts had access to metered data during simulation, see text.

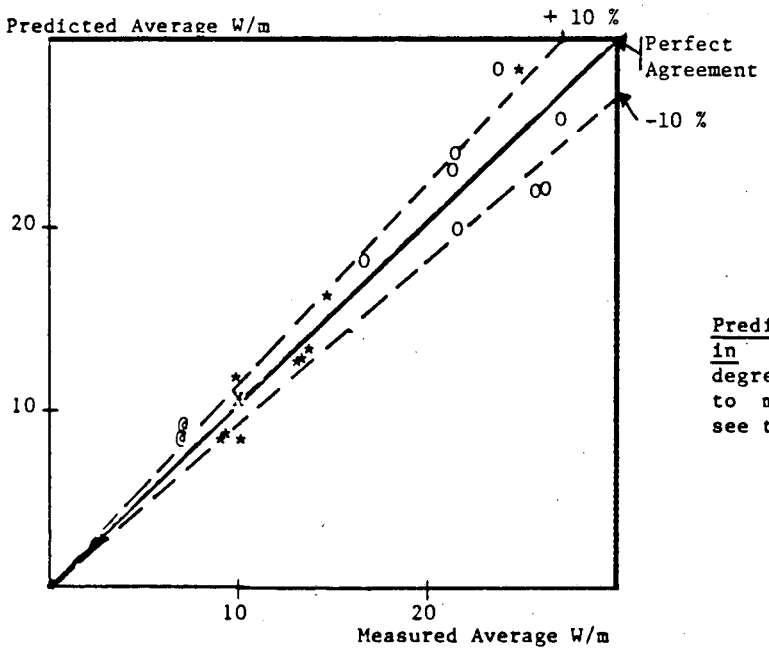


Figure 4

Predicted vs. Metered Site Energy Use in Non-submetered Buildings. For degree to which analysts had access to metered data during simulation, see text.

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