EVALUATION OF CALIFORNIA'S ENERGY EFFICIENT BUILDING STANDARDS: THE RESIDENTIAL BUILDING MONITORING PROJECT

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Abstract

The California Energy Commission has initiated an evaluation of its energy efficiency standards for residential buildings. A two year data collection and analysis project has been designed to calibrate and identify potential needed changes in the modeling assumptions used to determine the energy budgets required by the standards. The project will employ a three-stage nested survey using mail, on-site, and instrumented monitoring techniques to describe the physical and behavioral characteristics of new homes and their occupants.

This paper presents the research plan for the project and discusses methodological issues relating to the integration of broad coverage mail survey data with high resolution metering data. The analysis plan includes house-by-house comparisons of PRISM results with simulation model predictions, and conditional demand analysis that utilizes the metered data using a technique known as mixed estimation.

Introduction

The California Energy Commission (CEC) has been a national leader in developing innovative energy standards for new residential buildings for the past 10 years. During that time, the Commission has pioneered a number of building standards program features such as energy budgets and computer program certification. To complete this effort, the Commission has initiated an evaluation of its residential building standards program to assess its effect on energy use in new houses built throughout California.

The Residential Building Monitoring Project is a two-year data collection and analysis project designed to meet three primary objectives:

- Calibrate CEC-certified simulation models and validate the structural and behavioral input assumptions used to predict space conditioning and water heating energy use.
- Determine the mean space conditioning and water heating energy usage of new houses in various climate regions throughout the state.
- Determine the energy savings and cost-effectiveness of conservation measures encouraged by the building standards.

This paper presents the research plan for the project and discusses methodological issues relating to the conduct of a state-wide building standards program evaluation. Specifically, the paper addresses three main concepts:

- Prioritization of research objectives.
- Optimization of resources allocated to the project.
- Integration of data sources and research methods.

The first concept concerns the task of taking the initial research question that spawned the project — in this case, California Assembly Bill 191 in which the California Legislature posed the question, "Are these standards working?" and broke it into a set of research objectives that are reasonably quantifiable. The second concept — optimization of resources — relates experiences in developing a research plan tailored to meet multiple objectives. The final concept — integration — describes the leveraging and coordination of existing data sources, such as utility billing files and recent customer surveys, and the linking of the limited number of detailed monitoring sites to the broad-based mail survey data through the nested survey approach.

Project Background

The Title 24 building energy standards were adopted on a state-wide basis in early 1977. At that time, the Commission identified energy-efficient building and appliance standards as one of the most efficient and cost-effective means of saving energy. The evolution of the standards during the past decade has produced such innovative program features as life cycle costing, energy budgets, prescriptive packages, a simplified points system, computer program certification, and custom budgets.

The standards are performance based and stated in terms of allowable Btu consumption per square foot for space heating and cooling, and Btu per year for domestic water heating. Separate budgets have been developed for 16 different climate regions.[1] These energy budgets are typically 25% less than those of homes built before 1975. The level of energy efficiency required by the standards is driven by numerous assumptions about the physical and behavioral characteristics of new homes and their occupants. As with any pioneering endeavor, the development and refinement of the standards has relied on numerous sources for these assumptions. Committees established to "advise" the Commission on the design and implementation of the standards include building code officials, builders, architects, and private energy consultants. It is in these committees that many of the technical assumptions that drive the standards are derived. These assumptions include occupant behavior characteristics such as typical thermostat set-points and ventilation practices, and physical building characteristics such as building material thermal capacitance and resistance.

The development of the standards has relied extensively on simulation models to estimate both the house-specific and state-wide impacts of the building standards. Embedded in these models in the form of detailed algorithms are numerous assumptions about the behavioral characteristics of new home occupants and the structural attributes of new houses. To date, many of these assumptions and simulation model predictions have not been validated. Because of this, the California legislature has asked the CEC to gather field data of actual residential buildings to calibrate and identify potential needed changes in the modeling assumptions used to estimate the energy use of new homes.

Methodology

The research plan for the Residential Building Standards Evaluation Project utilizes numerous data collection and analysis techniques to achieve the project's multiple research objectives. The plan includes:

- A broad-based mail survey of approximately 2,400 new home owners.
- Detailed on-site inspections of a subset of 340 of the mail survey respondents.
- Detailed monitoring of a further subset of 40 homes in the on-site sample, including air infiltration monitoring, indoor and outdoor temperature measurements, and space and water conditioning appliance run-time metering.
- Conditional Demand Analysis (CDA) of the mail survey data to provide mean estimates of end-use energy consumption of new homes in four climate regions.
- Princeton Scorekeeping Method (PRISM) analysis augmented with a seasonal water heating adjustment factor for house-specific normalized consumption estimates for 340 on-site audited homes.
- Parametric simulation analysis using CALPAS3 of on-site sample homes to compare to PRISM estimates for determining the appropriateness of modeling assumptions.
- Cost estimation and cost-effectiveness evaluation of on-site sample homes.

Data Collection

The project employs an integrated three-stage data collection effort that includes a two-stage mail survey and billing data analysis of a broad-based sample of 2,400 new houses, on-site audits and computer simulations of a subsample of 340 of these houses, followed by instrumented monitoring of an additional 40 houses specially picked from the sample for their representative characteristics. This nested survey approach allows for increased precision in extrapolating the detailed data collected in the monitoring sample to the population through the on-site and mail samples. For example, the mail survey contains a list of questions that categorize thermostat behavior and set-points (*e.g.* manually turn on and off, leave at constant setting, programmed night-time set-back). These responses will be compared to the monitored thermostat behavior of households in the 40 home monitoring sample to both validate the mail survey responses and to determine the overall energy impacts of the different modes of thermostat operation.

Data collection will be carried out in four separate climate regions throughout the state. Each of these climate regions will be treated as a separate domain of study in the mail and on-site samples. Climate regions were defined by using proxy variables such as California Public Utility Commission (CPUC) Baseline Territories, a degree day-defined geographic segmentation of the state that is used for setting electric rate tiers. The climate regions are:

- Southern California Coastal Region
- Southern California Interior Valley
- San Francisco Bay Area Coastal Region
- Northern California Central Valley.

A smaller number of sample points will be allocated to the colder mountain regions of the Sierra Nevada in order to provide a basis for calibrating simulation model predictions in colder climates.

Mail Survey

The primary objectives of the mail survey are to:

- Provide data necessary for statistical estimation of space heating, cooling, and water heating energy usage by climate region through billing data analysis (Conditional Demand Analysis).
- Describe the typical energy-related behavioral characteristics of new home occupants (*e.g.*, thermostat set-points).
- Create the opportunity to segment and target selected subpopulations for the more expensive on-site and monitoring stages, thus increasing the efficiency of the sample.
- Expand the precision of estimates derived from the smaller on-site and monitoring studies.

The mail survey sample population of new, single-family homes was developed from the billing files of five California electric utilities:

- Los Angeles Department of Water and Power (LADWP)
- Pacific Gas and Electric Company (PG&E)
- City of Riverside
- San Diego Gas and Electric (SDG&E)
- Southern California Edison Company (SCE)

Various data elements in the utility billing records were used to identify the target population of new (*i.e.*, constructed after 1983 — the year in which the last significant changes to the standards took place), single-family homes, including meter set date (sometimes used in conjunction with a variable that identifies if the meter is new or a change-out), date-on-premises, customer control number, residential class code (identifying single- or multi-family), and apartment numbers in the service address. Both SCE and SDG&E had recently completed appliance saturation surveys and were able to supply us with samples of previously identified new, single-family homes drawn randomly from their survey populations. For the other utilities, a telephone pretest of the survey instrument showed an accuracy rate of approximately 75% for identifying new, single-family homes from the utility billing files. These customers were over-sampled accordingly.

The mail survey will be administered to new home owners that were selected randomly from each climate region. The survey instrument contains 68 questions pertaining to physical characteristics of the house such as appliance holdings, house size, conservation measures, and fuel types, as well as occupant behavioral characteristics including window management practices, use of shade screens, and thermostat set-points and operating profiles.

A two-stage mail technique was used to administer the survey. The survey package included a personalized letter with a printed signature from a CEC Commissioner, and a mechanical pencil as an incentive for filling out the questionnaire. The survey is presently in the field, with a first mailing response of approximately 40%.

On-site Survey

The primary objectives of the on-site survey are to:

- Collect detailed measurements of the physical characteristics of new houses (*e.g.*, conditioned floor-space, window areas, appliance nameplate data).
- Collect input data for simulation model calibration.
- Validate mail survey responses.

The on-site sample will be selected randomly by climate region from the population of mail survey respondents. However, because PRISM estimation is difficult for houses with end-use appliances such as wood stoves and swimming pools, households with certain appliance holdings will be excluded from this sample.

The on-site audits will provide detailed measurements of the ceiling and floor areas, wall and window areas by orientation, site shading, insulation levels, and appliance nameplate data (the latter to be cross-referenced with the Commission's appliance directories).

Monitoring

The primary objectives of direct monitoring are to:

- Obtain detailed measurements of factors affecting energy use such as ventilation rates, indoor air temperature, and thermostat behavior.
- Generate metered estimates of end-use energy consumption for domestic water heating and space conditioning.

The sample of 40 houses for the instrumented monitoring sample will be specially picked from the on-site sample. Each of the 40 houses will be monitored for a two month period. Single channel, battery powered data loggers will be used to collect the data.

Ventilation and infiltration rates will be determined through two methods: (1) blower door tests; and (2) long-term tracer gas concentration decay with perfluorocarbon tracer gas (PFT). The blower door tests will provide a static measurement of the effective leakage area of each house (a standardized measurement of the air tightness of the construction). The PFT test will measure the actual ventilation rate in the house (including all occupant behavior effects) for the two month monitoring period. These two methods will provide information on the air tightness of Title 24 homes, while also providing insights into the relationship between air tightness and overall air ventilation rates.[2]

Indoor temperature ranges, thermostat settings, and operation schedules will be measured using thermistors placed in two rooms of the house and in the supply duct of the HVAC system. Thermostat set-points can be determined by comparing the readings of these three measurement devices. The supply duct thermistor will indicate when the HVAC system is on or off based on the temperature differential between the living space and the duct. In this way, the indoor temperature at which the HVAC system is signalled on by the thermostat (*i.e.* the thermostat set-point) can be derived. Figure 1 shows the room and duct temperatures in a test home during a four day period. Figure 2 shows how a furnace on period can be derived for the morning of the second day. If we assume that the thermostat set-points are equal to the measured indoor temperatures during the time of furnace operation, we can derive the thermostat set-points in Figure 3 from the data in Figure 1. These estimated set-points are consistent with the programmed setbacks of the thermostat in the test house during the four day period, which was 70°F during the daytime with a setback to 60°F between 10:30 p.m. and 6:30 a.m. Note that in the mild California climate the indoor temperature never reached the setback temperature of 60°F and heating only occurred during the morning setup.

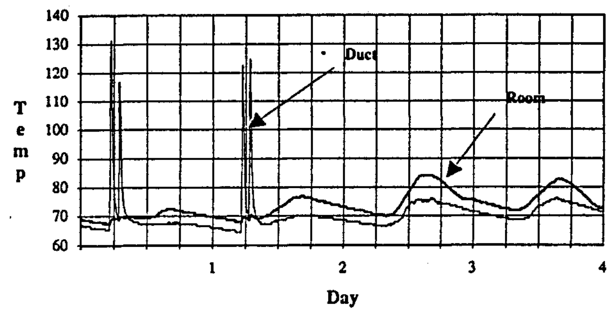

Figure 1. Living Zone and Duct Temperatures

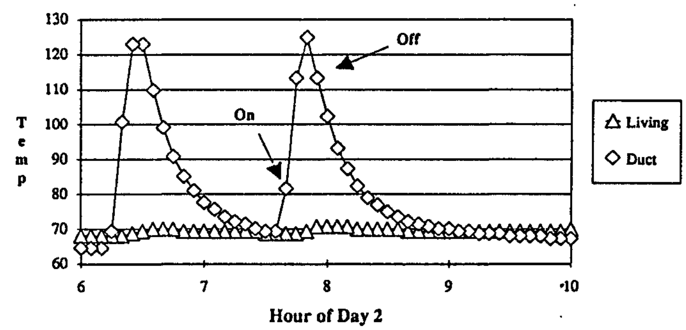

Figure 2. Living and Duct Temperature with FurnaceOn and Off Calculation

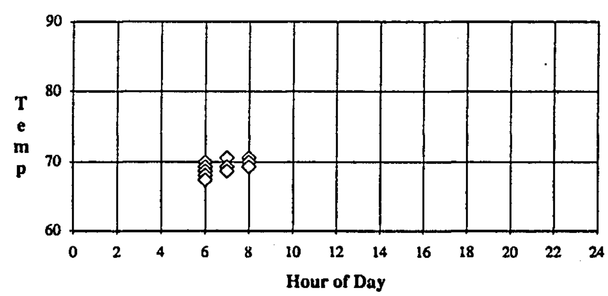

Figure 3. Living Space Temperaure When HVAC Running

Space heating and cooling and domestic hot water (DHW) energy usage will be calculated using two measurements: (1) the steady-state fuel consumption of the appliance measured during the initial equipment installation day; and (2) equipment run-time measurements recorded during the two-month monitoring period. Multiplying the fuel consumption by the hours of recorded operations yields the total energy consumption for the monitoring period. The space heating and cooling equipment run-time will be measured based on temperature readings from the thermistor in the HVAC supply duct (typical gas furnaces and air conditioners deliver conditioned air at approximately 140°F and 55°F, respectively). DHW energy consumption will be measured for gas water heaters by measuring the flue temperature from a thermistor placed in the exhaust stack.

Analysis Plan

The numerous issues being addressed in this project can be grouped into four main objectives:

1. Describe the typical physical characteristics of new homes.
2. Validate the input assumptions of the simulation models used to develop the building standards, including the physical building and occupant behavior characteristics of new homes in different climate regions.
3. Determine the mean space heating and cooling, and domestic water heating energy usage of new homes in different climate regions.
4. Determine the energy savings and cost-effectiveness of conservation measures encouraged by the standards.

The following describes the various levels of analysis designed to meet these objectives.

Description of Typical New Homes

California's residential building standards were developed through hourly heat load simulation analysis of prototypical houses in different climate zones. The characteristics of these prototypical houses were determined over the years in a somewhat *ad hoc* fashion. Because of the important role these model dwellings have in determining the appropriateness of measures enacted in the standards, a corroboration of these "typical" houses will be conducted. The on-site survey data will provide an excellent opportunity to revise the assumed typical characteristics of new houses for future development of the building standards. Random sample selection and a minimum sample size of 80 per climate region will ensure that representative mean parameter estimates of key variables such as house size and window area will be obtained for each climate region.

Validation of Input Assumptions

All of the CEC-approved simulation models[3] that are used to show compliance with the residential building standards rely on the same basic assumptions about the structural characteristics of the house (*e.g.*, steady-state air infiltration rate and window area by wall orientation) and the behavior patterns of the occupants (*e.g.*, internal gains from appliance usage, thermostat set-points, window operation). These assumptions, which have never been thoroughly validated, have a significant impact on the heating and cooling energy use predicted by the models. Therefore, a major focus of this project will be to validate and revise these important parameters.

The proposed research approach for input parameter validation and model calibration calls for two levels of analysis:

- Estimation of population means for input parameters derived from the mail, on-site and monitoring survey data.
- Determination of optimum set of parameters that yield the best fit between predicted and observed (PRISM) energy use based on parametric simulation analysis of on-site survey houses.

The first level of analysis will produce empirically-derived estimates of the "real" values of each of these parameters. The on-site survey data will provide most of the physical characteristics data, while the mail and on-site surveys will provide the required information on occupant behavior characteristics. However, because the relationship between these parameter values and the simulation model output are not linear, it is not certain that these population means will optimize the predictive capabilities of the simulation models. The key to this task, then, is to develop a set of input parameter values that allows the simulation models to best predict space conditioning energy use over a population of houses. Therefore, the model will be calibrated by altering the input assumptions until the model predictions best fit the observed (PRISM) estimates.

A problem with this approach is that PRISM does not specifically break out space heating and cooling from aggregate monthly bills. It separates weather-correlated loads from base loads. While the weather-correlated loads are predominantly related to space conditioning, they also include a portion of water heating energy use, as well as other loads such as cooking, lighting, and refrigeration.

To enhance the usefulness of the PRISM results, a seasonal water heating correction factor is being developed using metered data from PG&E's Appliance Metering Project (AMP). AMP contains hourly data on approximately 75 electric water heaters. This data will be analyzed to develop a monthly temperature adjustment factor for water heating. This will allow weather-sensitive water heating loads to be deducted from the weather-sensitive energy component of the PRISM estimates, resulting in a better estimation of space heating and cooling energy use.[4,5] Similar adjustments may be developed for other weather-correlated appliance loads as appropriate.

The proposed research plan includes house-by-house comparisons of simulation results derived from the detailed on-site audit data, and the house-specific space heating and cooling estimates derived from PRISM analysis of monthly utility bills and weather data. The on-site sample will be divided into two groups: the parameter estimation sample and the validation sample. Three-quarters of the sample will be used to re-estimate the optimum set of input parameter values. For each house in this group, a set of approximately ten simulation runs will be performed. For each run, the value of one or more of the key input assumptions will be varied, producing marginally different heating and cooling estimates. These estimates will then be compared to the original PRISM estimate. The optimum set of parameter values will be the set that minimizes the absolute difference between the simulated energy use and the PRISM-estimated energy use over the entire sample.

The new set of input assumptions derived through the parametric analysis will be tested on the validation sample. Once again, PRISM estimates will be compared on a house-specific basis to the simulation results using new and old parameter values. The results will be evaluated to ensure that the new values increase the accuracy of the model over the approximately 80 homes in the validation sample.

Determining Mean Space Conditioning and Water Heating Energy Usage

Mean space conditioning and water heating energy use will be estimated for each climate region through conditional demand analysis (CDA). CDA is an application of linear regression analysis where the dependent variable is the household's total annual gas and electricity energy use, and the explanatory variables are the characteristics of the house and its occupants — especially appliance stock — determined from the survey data. The name derives from the fact that total demand is conditional upon the ownership and utilization of specific end uses. The regression coefficients represent the average annual energy use associated with particular appliances. Thus CDA offers a way of estimating appliance end-use energy consumption from survey and billing data.

A technique known as mixed estimation will be used to add stability to the CDA estimates. This method adds "known" information (*i.e.*, end-use metered data) to the CDA data set in order to improve the model's ability to estimate end-use consumption. In this project, end-use data collected in the monitoring study will be added to the CDA analysis data set containing the mail survey and billing data. Each observation in the CDA data set contains the household survey data plus one month's weather plus one month's energy bills.

Determining Energy Savings and Cost-effectiveness of Typical Measures Encouraged by the Standards

Computer simulations of each of the 340 houses in the on-site sample will provide the basis for estimating the energy savings for conservation measures attributable to the standards. A series of baseline assumptions regarding the level of wall and ceiling insulation, structural characteristics, and the efficiencies of appliances installed in homes built before 1981 will be defined and used as the basis of the energy use comparisons in the simulation runs. Energy savings will be estimated by comparing the space conditioning and water heating energy use estimated of the new home (and calibrated to the actual bills) with the energy use of the same home using the pre-1981 level of conservation measures. Behavioral inputs such as thermostat setting will be the same for both runs.

The incremental costs of the conservation measures will be determined on a house-by-house basis by a professional construction cost estimation firm using current local material and labor cost estimates. These estimates will be used for the cost effectiveness analysis.

Results

The total project completion date is set for June 1990. The mail survey and CDA will be completed by August 1989. Monitoring and on-site surveys will begin in the Summer of 1989.

Endnotes

[1]***Energy Conservation Manual for New Residential Buildings.*** California Energy Commission, P-400-88-002, June 1988.

[2]J. O. Kolb and D. Baylon. "Evaluation of Infiltration in Residential Units Constructed to Model Conservation

Standards — Draft Report." Prepared by Oak Ridge National Laboratory for Bonneville Power Administration, November 1988.

[3]CEC-approved models include CALPAS3, CALRES, EasyCalc, MICROPAS, and TAKEOFF.

[4]M. F. Fels, *et al.* "Seasonality of Non-Heating Consumption and its Effect on PRISM Results," ***Energy and Buildings***, 1986.

[5]H. Hwang. "Assessment of Princeton Scorekeeping Method Space-Heating Estimates Using End-Use Data from the Hood River Conservation Project." Prepared by Oak Ridge National Laboratory for Bonneville Power Administration, March 1989.