Sources of Error in Home Energy Use Calculations: Evaluation in Real-World Laboratory Homes

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ABSTRACT

Energy simulation modeling and Home Energy Rating System (HERS) results are increasingly used in the design and implementation of energy efficiency programs. It is important therefore that these ratings be both repeatable and accurate. Previous studies have documented substantial uncertainty in the HERS results. The ability of the models to accurately estimate average energy use in the existing building stock has been called into question, and the studies have consistently found large variability in the simulation results relative to actual energy use for individual homes.

This carefully controlled study provides a detailed examination of HERS estimates relative to monitored heating and cooling energy use in four California homes. The study houses were unoccupied and extensively instrumented, with equipment schedules and internal loads controlled by computer. The houses varied in vintage, size, geometry, and shell characteristics. Each house was rated by six HERS raters and the resulting estimates were compared to each other, to simulation model estimates with inputs verified by the study team, and to monitored heating and cooling consumption of the homes.

The study found significant errors and variability in the HERS estimates. The models with inputs validated by the study team overestimated heating and cooling energy use at three of the four houses, with estimates more than double the monitored use in two cases. The results obtained from the HERS raters contained even larger overestimation and very large differences between raters. The raters' estimates were investigated to identify sources of errors and their relative contributions to the total.

Introduction

Energy simulation modeling of residential homes promises a number of benefits, but the effectiveness of the Home Energy Rating System (HERS) has been hampered by a history of poor performance and insufficient field research to inform improvements to the models and procedures. One of the challenges has been uncertainty regarding the sources of error. There is large variance in the residential building stock and even two houses that appear identical may have hidden differences that significantly alter their energy consumption characteristics. Occupant behavior is highly variable and difficult to control for. HERS practitioner behavior is also highly variable, and a number of critical inputs to the simulation models are subject to measurement error or "best guess" estimates. Even if errors can be identified as systematic, energy simulation software packages contain proprietary algorithms and assumptions, making it difficult for third party reviewers to identify the root cause.

This study performed a detailed investigation of HERS estimates at four California homes. Uncertainty was reduced by using unoccupied homes with internal loads controlled by computer. Building characteristics were thoroughly investigated by the research team. The homes were monitored during one cooling and one heating season, and the results were compared to estimates from multiple HERS raters, and to estimates from a HERS model with all inputs validated by the research team.

Background

Reliance on energy simulation models in the design, implementation and evaluation of energy efficiency programs for residential buildings has grown in recent years. As the use of these tools has expanded, questions remain regarding the reliability of their results. To some degree, their reliability is dependent upon the intended application. High level program planning and policy decisions may be adequately informed by simulations with substantial uncertainty in the results for individual homes as long as the average is representative of the general population. On the other hand, homeowners seeking advice on costly home improvement projects require very accurate predictions specific to their individual house to ensure their investments are worthwhile. There are also differences between new construction vs. existing building applications, and high end custom projects vs. efficiency programs directed toward the mass market.

Multiple studies have raised concerns regarding the accuracy of commonly used simulation software packages, particularly when applied to existing homes. The studies have documented a tendency to overestimate energy consumption in existing homes and generally poor correlation between the simulation model results and energy bills (Stein 1997, Wilcox and Hunt 1998, Pigg and Nevius 2000, and Earth Advantage Institute and Conservation Services Group 2009).

The studies have also documented significant scatter in the results, suggesting that even if the simulation models are capable of accurately representing average energy use for a large population of homes, the results for individual homes remain uncertain. This is true even in new construction where the simulation inputs can be known with much more certainty than for existing buildings. A study of a large sample of new homes in the Houston area (Hassel, Blasnik and Hannas 2007) found excellent agreement on average between modeled and actual cooling energy use, but with substantial scatter among individual homes (Figure 1).

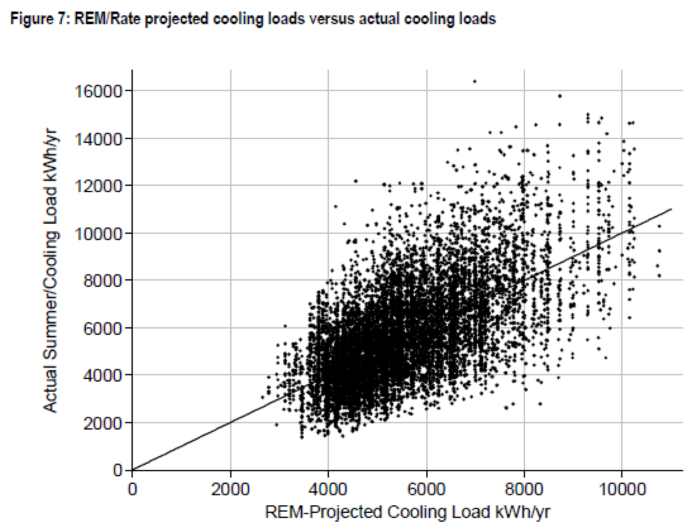

Figure 1. Simulated vs. Actual Cooling Load in New Homes (Hassel, Blasnik, and Hannas 2007)

These studies raise concerns about the reliability of energy savings estimates for efficiency programs based on simulation models, as well as the quality of home improvement advice provided to individual homeowners who are being asked to make substantial investments under these programs.

A recent impact evaluation of California energy efficiency programs designed around and heavily dependent upon energy simulations for savings estimation and decision making in individual homes found realized energy savings well below the expected values (DNV GL – Energy 2014). The evaluation of California whole house retrofit programs studied multiple programs that served over 4,000 homes between 2010 and 2012. The study found gross electric energy savings for the “Advanced Path” programs ranging from 13% to 50% of expected values, and gross natural gas savings ranging from 36% to 63% of expectations. Cumulatively, the gross realization rates for these programs were 18% for electric and 40% for gas energy savings. Uncertainty in the energy simulation results was cited as a potential factor contributing to the shortfall.

Recent investigations into the accuracy concerns have identified some potential sources of errors within the models themselves, as well as challenges related to model inputs. When provided with extremely detailed information including behavioral energy use characteristics, simulations can be made to produce results that are quite accurate (Parker et al. 2012). However, it is not certain that HERS raters are capable of obtaining such detail, or that it would be cost effective to do so in a mass market efficiency program.

Methodology

This study was a task in the Central Valley Research Homes (CVRH) project (Proctor and Wilcox, Draft) funded by the California Energy Commission Public Interest Energy Research (PIER) program. The CVRH project continuously monitored four single family homes in Stockton, CA for three years. The first year of monitoring documented the original condition of the houses. Years two and three measured the energy impacts of various improvements. This paper compares the first year (original condition) monitored heating and cooling energy use to estimates obtained from multiple HERS raters.

The study houses varied in vintage from 1948 to 2005, from 852 to 2076 square feet, and included a variety of foundation types, number of stories, window types, HVAC systems, and building shell characteristics. The energy performance attributes of these homes cover a range typical of existing houses in California.

Prior to monitoring, each house was rated by six HERS raters. The raters were not informed of the project or that multiple ratings were being collected at each house. A HERS simulation was also performed by the study team, with each input carefully checked to ensure the closest possible match to the existing condition in the house. The resulting cooling and heating energy use estimates were compared to each other, and to the monitored results.

The houses were unoccupied, with equipment schedules and internal loads controlled by computer. Each house was fully instrumented to continuously monitor heating, cooling, and total energy use as well as temperature and other indoor and outdoor environmental conditions. Data were downloaded and reviewed daily to ensure proper operation of all sensory and control equipment.

Monitoring and Control Equipment

The houses were extensively instrumented, including the data points shown in Table 1. The monitored data points were read every 20 seconds and the average (or sum as appropriate) was recorded every minute. The monitored data included energy use and operational status of the space conditioning equipment as well as environmental conditions outside and throughout the house. The houses were operated under controlled conditions that simulate normal internal gains as defined in California's Residential Building Energy Efficiency Standards (Title 24). The thermostat settings were also matched to the Title 24 definition to produce load patterns similar to an average residence.

Table 1. Monitored Data Points

Category	Item	Category	Item
Energy Used	Total House kWh	Heating/Cooling	Thermostat Set Point
Energy Used	AC Outside Unit kWh	Heating/Cooling	Thermostat Call Status (each zone)
Energy Used	AC Inside Unit kWh	Heating/Cooling	Air Handler Status (on/off)
Energy Used	Furnace Natural Gas (ft^3)	Heating/Cooling	Furnace Status (on/off)
Ambient	Outdoor Ambient Temp	Heating/Cooling	AC Condensing Unit status (on/off)
Ambient	Outdoor Ambient Humidity	Heating/Cooling	Room Temperatures (each room)
Occupancy Simulator	Latent kWh	Heating/Cooling	Temperature (each thermostat)
Occupancy Simulator	Sensible kWh	Heating/Cooling	Humidity (each floor)

Description of Homes

The study homes included a range of building styles and vintages common to the Central Valley region of California. Characteristics of each home are summarized in Table 2.

Table 2. Characteristics of Study Houses

Caleb	Built in 2005, 2,076 ft^2, 4 bedroom, 2 story, rectangular with a portion of the second story overlapping the garage, slab on grade
Insulation	R-30 attic, Walls are approximately R-17 (R-13 in wall cavity + R-4 exterior foam sheathing)
Windows	Vinyl, double-pane, low-E
House Leakage	1494 CFM50 (5.0 ACH50)
Duct System	Zoned (2) attic duct system, R-6 insulation, leakage 13.3% of nominal airflow
Air Conditioner	4 tons, 10 SEER, 9.25 EER
Heating System	90,000 BTU/hr 0.80 AFUE gas furnace
Fedelia	Built in 1996, 1,690 ft^2, 4 bedroom, 2 story, complex footprint with numerous angles, slab on grade
Insulation	R-30 attic, R-13 walls
Windows	Aluminum with vinyl cover strip, clear double-pane
House Leakage	1626 CFM50 (7.2 ACH50)
Duct System	Ducts in attic and between floors, R-4.2 insulation, leakage 13.4% of nominal airflow
Air Conditioner	3.5 tons, 10 SEER, 9 EER
Heating System	88,000 BTU/hr 0.80 AFUE gas furnace
Mayfair	Built in 1953, 1104 ft^2, 3 bedroom, one-story, rectangular, vented crawlspace
Insulation	Approximately R-7 attic, no wall cavity insulation
Windows	Steel casement, single pane
House Leakage	1,437 CFM50 (9.8 ACH50)
Duct System	Attic ducts, R-6 insulation, leakage 10.7% of nominal airflow
Air Conditioner	2.5 tons, 13.2 SEER, 11.5 EER rooftop packaged unit
Heating System	70,000 BTU/hr, 0.805 AFUE gas packaged unit
Grange	Built in 1948, 848 ft^2, 2 bedroom, single-story, rectangular, slab on grade
Insulation	Attic and walls have layers of accordion foil paper, R-value estimated to be near 0
Windows	Aluminum, single-pane
House Leakage	762 CFM50 (6.7 ACH50)
Duct System	Attic ducts, R-4.2 insulation, leakage 8.2% of nominal airflow
Air Conditioner	2.5 Tons, 10.45 SEER, 9.5 EER
Heating System	50,000 BTU/hr, 0.80 AFUE gas furnace

HERS Rater Testing

The project team attempted to carry out a blind comparison of the four homes. A member of the research team who is an architect contacted HERS raters listed as active in the project area and requested HERS ratings for an unspecified client. The architect requested standard HERS ratings on each of the four houses and paid the rate requested by each rater. A total of six HERS raters were contracted to provide ratings on each of the four homes.

The HERS raters were not informed that their work was part of a research project or that other raters would be rating the same house. The ratings were performed prior to the installation of monitoring equipment or any other work being done at the house. Rater visits were scheduled to avoid contact with other raters. The work was presented to the HERS raters as an ordinary job. Some challenges were encountered in maintaining the blind comparison, including visibility in the HERS Provider registry that other raters were active at the same homes. Overall, the research team is confident that the study was sufficiently blind to have captured a typical representation of the HERS rating process.

The HERS raters all used version 5.1.6.7 of Energy Pro.

Analysis of Monitored Data

Monitoring of the houses in their original condition began in August, 2012 and continued until April, 2013. Monitored data were downloaded, analyzed and reviewed daily. Anomalies were investigated by site visits, and days that were found to have unreliable data due to monitoring and control equipment malfunctions or physical problems such as broken windows were excluded from the analysis. The daily review process enabled the research team to rapidly detect and remedy problems without large loss of data or uncertainty regarding data integrity. Overall, 5.9% of cooling days and 6.5% of heating days were excluded based on the review and investigation process.

There were two HVAC systems at each house: the original system, and a secondary system that was installed as a reference point for other analyses being conducted under the study. Both systems were standard residential air conditioners and were controlled to the same set points. The monitoring and control system toggled between the two HVAC systems every four days, meaning that 50% of the monitored days were available for analysis of the heating and cooling energy use of the house with the original HVAC system that was in place at the time of the HERS rating.

The monitored cooling and heating energy use with the original HVAC system were modeled by linear regression as a function of daily average outdoor temperature, as shown for the Caleb house in Figure 2. The regressions produced R^2 values above 0.9 in all cases except for Grange cooling (0.77) and Mayfair cooling (0.85). The resulting regressions were then applied to the California Title 24 weather file to develop annual cooling and heating energy use estimates normalized to the same weather assumptions used in the simulation model. The 2008 version of the Title 24 weather file was effective at the time of the HERS ratings, and was used for normalization of the monitored energy use for comparison to the HERS estimates.

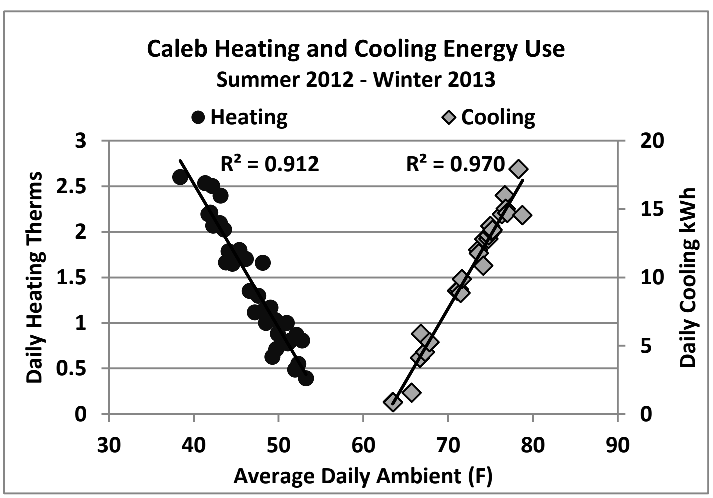

Figure 2. Heating and Cooling Energy Use at the Caleb Home

Analysis of HERS Estimates

The research team developed HERS models for each house, with each input carefully validated against the documented characteristics of the house. These Validated Models represent the best possible outcome from the simulation software. Systematic Error was calculated as the difference between the Validated Model outputs and the weather normalized monitored heating and cooling use. Percent Systematic Error was calculated as Systematic Error divided by the measured energy use.

Detailed files were obtained from 5 of the 6 HERS raters. These files were compared to the results of the Validated HERS models to identify predominant sources of input error. Based on this preliminary investigation, the model inputs were categorized into 8 groups. The input categories were defined as groupings of related items where one or more of the items in the group was likely to be significant source of error for one or more raters. For example, duct leakage and building shell leakage were grouped together into the “Air Leakage Measurements” category.

The models obtained from the HERS raters were iteratively modified to correct errors in a single category without modifying other inputs. This process produced 40 variations of the simulation model for each house. The heating and cooling energy use from these 40 variations were then compared to outputs from the Validated model to determine the magnitude of errors attributable to each category of inputs. User Error for each category was calculated as the difference in predicted energy use between the original model provided by the HERS rater and the modified model with corrected inputs in a given category.

$$\text{Error}_{i,j} = \text{Energy Use}_{i,\text{Original}} - \text{Energy Use}_{i,j}$$

Where i indicates the individual HERS rater, and j indicates the input category that was modified to match the Validated model.

Input errors can produce complex interactive effects in the simulation models. The research team did not attempt to evaluate the magnitude of these interactions or the magnitude of individual errors absent any interactions, instead taking a top down approach starting with the original model provided by the HERS rater and all errors and interactive effects contained therein.

Results

Limitations and Uncertainty

This study was designed as a very focused and detailed investigation. As such, the sample size was necessarily small. The results provide insight into the HERS rating process for existing homes in California but are not intended to represent a statistically significant characterization of universal systematic errors within the simulation software, or to draw broad conclusions regarding efficacy of the HERS models in other regions.

Sources of uncertainty include:

- The study houses were unoccupied, without furniture. This affects thermal mass and latent storage in the home, potentially affecting space conditioning energy use.
- The monitoring equipment included small aspirator fans for the temperature sensors in each room. Fans were also used with the heaters for internal load simulation. This potentially increases air mixing relative to a typical home.
- There are three issues related to internal gains:
    1. The control software programming delivered total internal gains that were slightly lower than intended. The difference averaged 1.6% in summer and 5.8% in the winter.

2. A more significant source of uncertainty results from differences between the 2013 and 2008 versions of the California Title 24 specifications and HERS Technical Manual. The 2008 language specifies internal gains with no guidance as to sensible and latent contributions. The 2013 language specifies the same total internal gains as in 2008, but with sensible and latent components for some items. The house control system was programmed to the 2013 assumptions, while the HERS software was compliant with the 2008 language. This raises the possibility that the HERS software sensible vs. latent assumptions may differ from those used in the occupancy simulation programming.
3. Latent gains in the houses were disabled during the heating season due to concerns about moisture buildup. All of the internal gains were delivered as sensible.

The research team established bounds on the uncertainty associated with internal gains based on the difference between the delivered sensible gains and possible interpretations of what the sensible gains should have been. For example, if the 2008 specifications were interpreted to mean that all of the internal gains should be sensible then the cooling load would be increased. It was then assumed that 100% of the possible difference in sensible gains would directly impact heating and cooling loads, at the rated efficiency of the heating and cooling equipment.

Accuracy of HERS Estimates

The cooling and heating energy use estimates from the individual HERS raters in comparison to the monitored use and estimates from the Validated models are shown in Figure 3. As previously discussed, differences in delivered internal sensible gains vs. assumptions in the simulation models present a potentially significant source of uncertainty. Bounds on the possible impacts are shown as error bars on the monitored use.

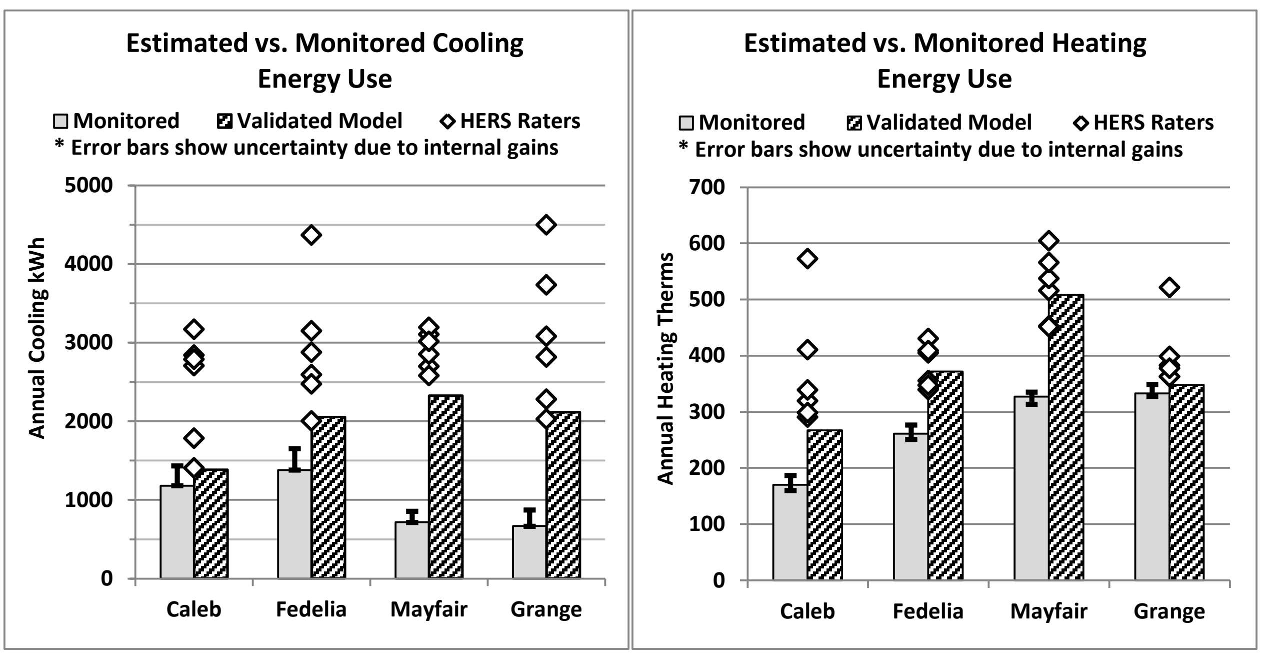

Figure 3. Monitored and Estimated Cooling and Heating Energy Use

The HERS rater results are highly variable and display a bias toward overestimation compared to the Validated model. The range between the highest and lowest HERS rater estimates of cooling energy use exceeds 100% of the Validated model estimate for three of the four houses. Heating predictions are somewhat better, with the range of estimates exceeding 100% of the Validated model result for just one house (Caleb), and the remaining three houses at less than 50%. These results are clearly less than optimal from the viewpoint of homeowners or efficiency program administrators seeking consistent feedback from the HERS rating process, and suggest that large estimation errors related to user inputs are common.

Even with validated inputs, the simulation models tend to overestimate cooling and heating energy use. Validated model estimates are within 20% of the monitored cooling use in one case (Caleb), but exceed the monitored use by more than 200% in two cases (Mayfair and Grange). Heating use shows closer agreement, with the Validated model estimate within 5% of monitored use in the best case (Grange), and exceeding monitored use by 43% to 57% in the remaining three houses. The impact of uncertainty in the sensible internal gains is larger for cooling than for heating, and would potentially change the outcome in only one case (Caleb cooling).

The combined effects of HERS rater inputs and simulation model overestimation produced extremely large errors. Cooling energy use was overestimated by as much as 600% (Grange), and heating use was overestimated by as much as 200% (Caleb).

Evaluation of HERS Rater Error Sources

Results of the HERS rater input error analysis are shown in Figures 4 and 5. Each rater's results for each house are displayed. Rater errors are presented as a percent of the Validated model estimated use for cooling and heating. Due to interactive effects, the sum of the individual errors by category does not necessarily equal the overall error in each rater's estimate. For reference, the overall error is superimposed on each rater's results.

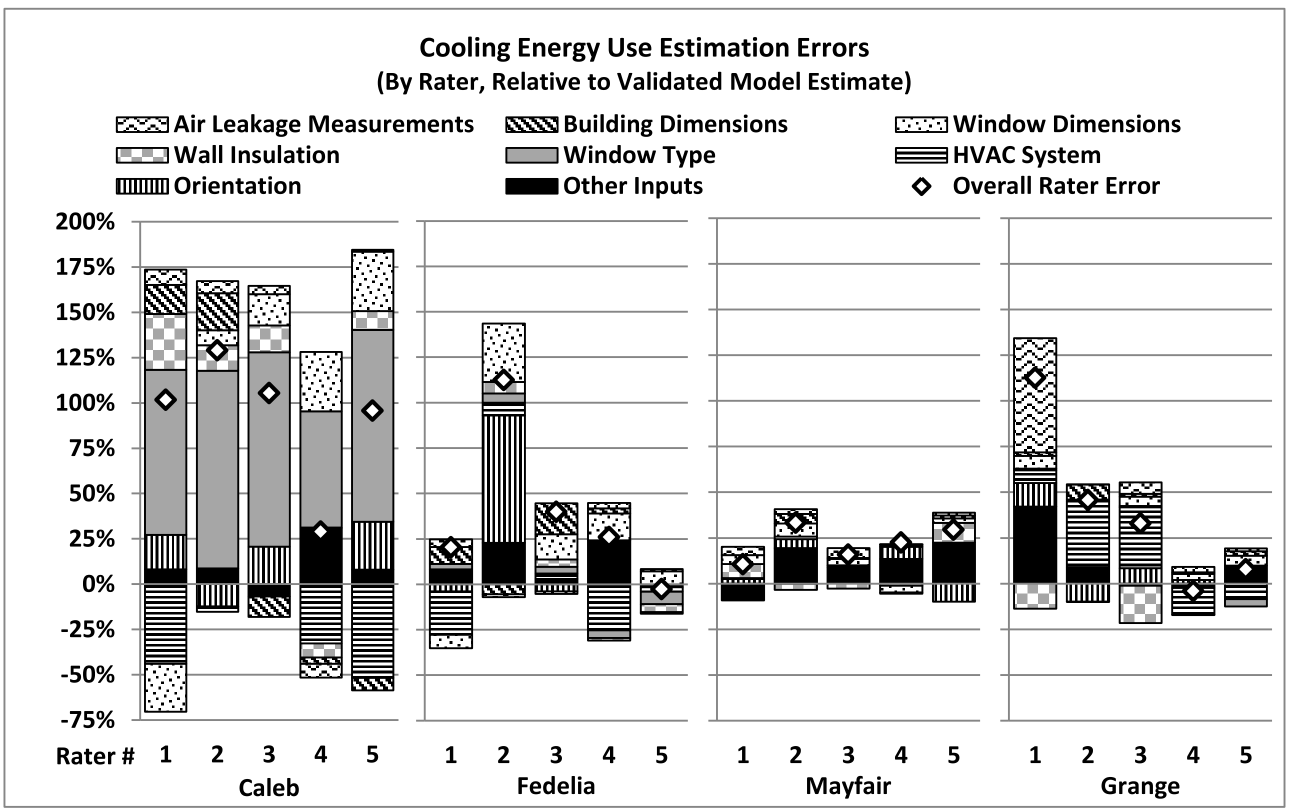

Figure 4. Cooling Energy Use Estimation Errors by Rater, House, and Input Category

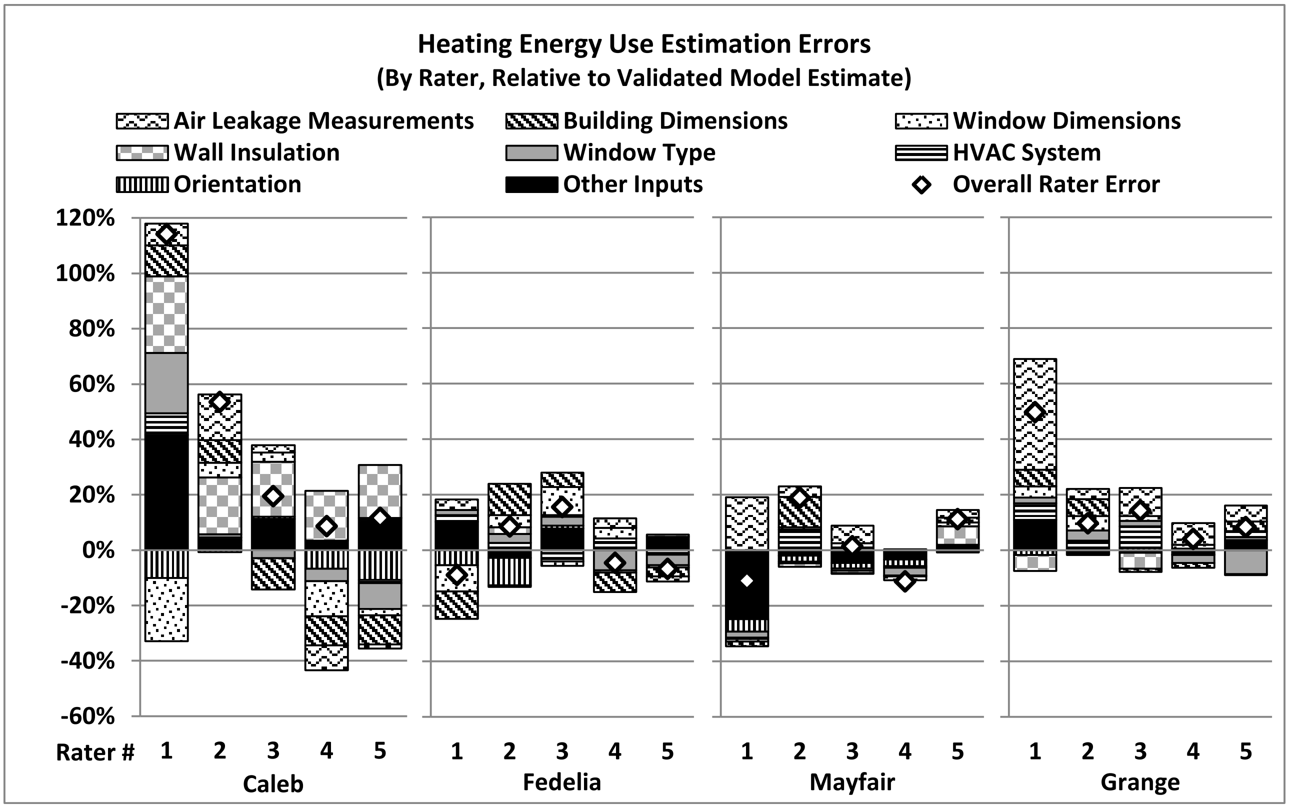

Figure 5. Heating Energy Use Estimation Errors by Rater, House, and Input Category

There is no clear evidence that the raters differed substantially in their performance. All of the raters made significant errors at one or more houses, and all produced reasonably good estimates at one or more houses. There were some common themes among error sources, with most raters making similar incorrect assumptions about windows and wall insulation at the Caleb house. Air conditioner efficiency was a common source of error among raters at three of the houses. Efficiency is typically not indicated on the air conditioning unit nameplate, and it can be challenging to find information for older units. It is clear that guesswork or default assumptions are often used to determine HVAC system efficiency, and can have a large impact on the space conditioning energy use estimates.

Notable input errors by house include:

All Houses

- Orientation errors were surprisingly common, and in the most severe case increased the cooling use estimate at the Fedelia house by 75%. This category includes cases where the orientation for the entire building is incorrect, as well as cases where some aspects of the building geometry were incorrectly laid out, causing windows or other features to be modeled on the wrong side of the building.

Caleb

- Most raters assumed the windows were single pane clear glass. They are actually double pane low-E.
- Most raters assumed R-13 wall insulation, neglecting the additional layer of R-4 foam sheathing.
- Three of the raters listed the air conditioner as a SEER 13. It is actually SEER 10.

- Window areas were over or understated by most raters. In some cases, all windows in a room were omitted. On other cases all windows in an area were input as one large window, but the area didn't match the sum of the areas of the actual windows.
- One rater assumed a raised floor foundation. It is actually slab on grade. (This is included in the Other Inputs category.)

Fedelia

- Two raters assumed a SEER 12 air conditioner. It is actually SEER 10.
- Window areas were overstated by most raters.
- Two raters assumed an unvented attic. It is actually vented.
- One rater modeled the house as a single story. It is actually two stories.
- One rater included an unconditioned sun room in the conditioned space.

Mayfair

- One rater assumed slab on grade foundation. It is actually a vented crawlspace.
- One rater input 4242 CFM50 shell leakage. The research team measured 1437 CFM50.
- Most raters neglected overhangs and exterior shading. (This is included in the Other Inputs category.)

Grange

- Two of the five raters listed the air conditioner efficiency as SEER 8, while another rater listed it as SEER 12. It is actually SEER 10.4.
- One rater input 59% duct leakage. The research team measured 10%.
- One rater assumed a raised floor foundation. It is actually slab on grade. (This is included in the Other Inputs category.)

Conclusions

The study found poor agreement between HERS cooling and heating energy use estimates and monitored energy use at the four test houses. The following issues were noted:

- The calculations tended to overestimate heating and cooling energy use. The models with inputs validated by the study team overestimated use in 3 of 4 cases.
- HERS rater input errors increased the overestimation, resulting in overstated heating and cooling use in all cases.
- There was large variance in the HERS raters' results, with individual raters producing estimates as high as 6 times the monitored energy use.
- Errors were widespread across all categories of inputs. Even obvious items such as foundation type were input incorrectly.
- Erratic performance appears to be the norm. There was no indication that individual raters were better or worse than their peers.

Given the variability of the HERS results observed in this study as well as the sources and magnitude of errors, the reliability of the HERS process in informing improvement decisions in individual existing homes is questionable. For example, the HERS ratings indicated that large energy savings could be accomplished in the Caleb house by upgrading the windows. In fact, the existing windows were already efficient double pane low-E glass. Replacing them would have been a costly project with little or no energy savings.

Recommendations

Energy efficiency program planners should carefully consider the demonstrated capabilities of energy simulation tools and processes relative to the needs of their programs prior to specifying HERS or other simulation modeling as an implementation strategy. Modeling existing residential buildings presents many challenges and this study did not find evidence that the results for individual houses are accurate or repeatable.

Program planners should seek simple solutions for the sake of both accuracy and cost. Within the context of energy efficiency programs aimed at improving existing homes, it is not clear that attempting to collect a large amount of uncertain information and process it through a complex simulation model is the most effective approach. This study did not find evidence that the value provided by the HERS process outweighs the considerable labor and administrative costs to efficiency programs. Homeowners and the general public funding these programs might be better served by simplified and more targeted approaches with a focus on obtaining accurate information regarding specific areas for improvement.

Quality assurance improvements to the HERS process should be investigated. The human element is as important to the process as the underlying algorithms. Approximately half of the average heating and cooling use overestimation in this study resulted from input errors.

Continued research to evaluate and improve the building simulation models is needed. Correlation to real-world empirical data is a critical step that has been neglected in the past. Despite studies dating back more than a decade and a half showing poor agreement between simulation model outputs and utility bills, the problems have still not been fully addressed. Since this study was conducted, an updated simulation model has been implemented in California. Ongoing field research is needed to evaluate its performance and inform future improvements.

Acknowledgments

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