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Assessing the value of information in residential building simulation: Comparing simulated and actual building loads at the circuit level

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HIGHLIGHTS

- 106 homes are simulated in EnergyPlus using energy audit and survey records.
- Simulation results are compared to monitored data at the device level.
- Modeling reveals large discrepancies between simulated and actual energy use.
- Sensitivity analysis is used to identify factors most important for accurate models.
- The role of EnergyPlus in residential energy code design and analysis is discussed.

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ABSTRACT

Building energy simulation tools are now being used in a number of new roles such as building operation optimization, performance verification for efficiency programs, and – recently – building energy code analysis, design, and compliance verification in the residential sector. But increasing numbers of studies show major differences between the results of these simulations and the actual measured performance of the buildings they are intended to model. The accuracy and calibration of building simulations have been studied extensively in the commercial sector, but these new applications have created a need to better understand the performance of home energy simulations.

In this paper, we assess the ability of the DOE's EnergyPlus software to simulate the energy consumption of 106 homes using audit records, homeowner survey records, and occupancy estimates taken from monitored data. We compare the results of these simulations to device-level monitored data from the actual homes to provide a first measure of the accuracy of the EnergyPlus condensing unit, central air supply fan, and other energy consumption model estimates in a large number of homes. We then conduct sensitivity analysis to observe which physical and behavioral characteristics of the homes and homeowners most influence the accuracy of the modeling.

Results show that EnergyPlus models do not accurately or consistently estimate occupied whole-home energy consumption. While some models accurately predict annual energy consumption to within 1% of measured data, none of the modeled homes meet ASHRAE criteria for a calibrated model when looking at hourly interval data. The majority of this error is due to appliance and lighting energy overestimates, followed by AC condensing unit use. These inaccuracies are due to factors such as occupant behaviors and differences in appliance and lighting stocks which are not well-captured in traditional energy audit reports. We identify a number of factors which must be specified for an accurate model, and others where using a default value will produce a similar result.

The use of building simulation tools reflects a shift from a component-focused approach to a systems approach to residential code analysis and compliance verification that will serve to better identify and deploy efficiency measures in homes. By better understanding the limitations of home energy simulations and adopting strategies to mitigate the effects of model errors, simulation models can serve as valuable decision making tools in the residential sector.

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1. Introduction

Increased attention to building energy performance, improved software packages, and decreasing computing power requirements have led to the use of building energy simulation tools in a large and growing number of applications [1–3]. These tools are now being used in their traditional role as decision support for building and retrofit design in the commercial sector, but also in new roles such as building operation optimization [1], performance verification for energy efficiency programs like LEED [4], and – recently – building energy code analysis, design, and compliance verification in the residential sector [3,5]. However, increasing numbers of studies show major differences between the results of these simulations and the actual measured performance of the buildings they are intended to model [6–13]. These discrepancies, combined with the new application of building simulation tools to policy and investment decision-making in the residential sector, have created a need to better understand the accuracy of their results and develop methods for calibrating them to ensure reliable outputs. Doing so will allow policymakers to apply these tools in a way that will ensure that residential building energy codes continue to deliver the energy savings for which they are intended.

The Department of Energy's EnergyPlus is the most prominent simulation package being used in these new residential applications. As part of their work for the Building Energy Codes Program, Pacific Northwest National Laboratory (PNNL) established a method for analyzing potential changes to residential building codes based on EnergyPlus [3]. The method first involved the construction of prototype EnergyPlus models of simple single- and multi-family residences that meet existing region-specific building codes. The cost-effectiveness of potential changes to these codes is evaluated by incorporating a proposed change in the model – reducing allowable building leakage rate, for instance – simulating the building's energy performance using local weather data, and observing the resulting change in energy consumption. The simulated energy cost savings are then compared to the first cost to estimate the lifecycle cost of implementing the change. These results then serve to inform the DOE's position on whether to approve a code change proposed by the International Code Council (ICC), but are also used to inform state and local jurisdictions about the expected effects of adopting a new code when they are considering a change.

EnergyPlus is also in the process of being incorporated into a tool being developed by the Residential Energy Services Network (RESNET) to standardize residential energy benchmarking for energy code compliance. RESNET is a not-for-profit membership corporation that develops standards used in home energy efficiency ratings [14]. RESNET's Home Energy Rating System (HERS) is an industry standard calculation specification that allows certified energy raters to assign efficiency scores to homes that can be used to demonstrate their energy code compliance in most states and jurisdictions [5,15]. Efficiency scores are currently calculated using any one of a number of software programs that have been approved and accredited by RESNET [16]. In March of 2016, however, RESNET and the DOE announced that this suite of software packages is going to be replaced by a single-source tool based on EnergyPlus [5]. While the tool has not yet been released or described in detail, its announcement alone highlights the need to better understand the ability of EnergyPlus to accurately model residential buildings.

Each release of EnergyPlus is thoroughly validated using three types of methods [17]. Analytical verification compares EnergyPlus results to mathematically determined results for individual building components and systems. Comparative testing compares EnergyPlus simulation results to the results of other simulation packages. These two validation methods are described in a variety of technical standards including ANSI/ASHRAE Standard 140, *Method of Test for the Evaluation of Building Energy Analysis Computer Programs*. Finally, empirical validation compares simulation results with measured energy consumption from actual buildings.

Previous empirical studies of the accuracy of building energy simulations have focused almost exclusively on the commercial sector and have often found large discrepancies between modeled and actual performance. These studies typically involve the construction of a model of a building in which extensive data gathering has been conducted. Using measured and observed details of the building and its operation, a detailed model is constructed and its simulated performance is compared to measured data such as electric or gas utility data [10,17], environmental sensor data [11], or submetered system-level data [8,12,13]. Models are often then modified to observe the effects of varying certain parameters to observe their effect on simulated energy consumption [17]. Based on these results, conclusions are drawn about which parameters are most important to specify and the suitability of the chosen model and application, and recommendations are made to improve modeling efforts in the future. The results of some of these comparison studies have called into question the basic ability of simulation tools to predict energy use in buildings given all of the uncertainties involved in building an accurate model [17].

In addition to empirical validation efforts, there are a growing number of papers dedicated solely to the methods by which these models can be calibrated. Coakley et al. summarized these methods in a literature review of around 70 papers addressing issues of calibration in building simulation modeling [18]. The authors propose four classes of calibration methods: (i) calibration based on manual, iterative and pragmatic intervention, (ii) calibration based on a suite of informative graphical comparative displays, (iii) calibration based on special tests and analytical procedures, and (iv) analytical and mathematical methods of calibration. The paper generally finds no consensus method for building simulation calibration, nor does it find a widely accepted set of criteria for validating these models. However, given the large body of literature found by the authors, they conclude that the work already available could inform the development of standardized methods for model calibration. Recently, attention has turned to the development of automated model calibration methods that rely less on modeler expertise and more on mathematical and analytical approaches [19]. These methods generally use optimization tools to minimize an error term between simulated and actual data by tuning specified model parameters [8,19].

Both empirical validation studies and calibration studies are typically limited by data availability to a small number of buildings. The conclusions that can be reached from such studies are therefore limited as well. To address this issue and increase sample sizes, research is now turning to batch simulations in which large numbers of buildings are modeled in parallel. Rhodes et al. used one such method to simulate 54 homes in the Pecan Street study using energy audit and survey records as model inputs [20]. A baseline model of each home was built using actual building characteristics and simulated using Typical Meteorological Year (TMY) data. Three alternate scenarios were then simulated which (1) used actual weather data, (2) updated default thermostat settings with actual thermostat settings, and (3) simplified each home's geometry into a rectangular footprint. Each set of simulation results were compared to measured whole-home annual electricity consumption. Results indicate that including actual thermostat settings improves model accuracy, actual weather data unexpectedly worsened accuracy, and simplifying home geometries had little effect on outcomes. Errors for individual homes ranged from underestimating actual annual consumption by 60% to overestimating by