Energy and Buildings 69 (2014) 535–543

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Comparing the effectiveness of weatherization treatments for low-income, American, urban housing stocks in different climates

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ARTICLE INFO

Article history:
Received 4 November 2012
Received in revised form
23 September 2013
Accepted 8 November 2013

Keywords:
Weatherization
Low-income housing
Building energy modeling

ABSTRACT

This paper presents and demonstrates a method for evaluating how the effectiveness of weatherization treatments varies geographically due to difference in climate and housing stock. American Housing Survey data was used to describe the low-income urban housing stock in six different cities representing a range of geographical and climatic areas. These data were then used to drive the Home Energy Saver model to simulate current energy consumption and expected energy savings from a combination of three weatherization treatments: replacing a standard thermostat with a programmable thermostat, installing attic insulation, and envelope air sealing. Modeled energy savings were compared to observed energy savings. Results show that greater energy saving potential generally exists in cities with colder climates, but the effectiveness of different weatherization treatments also varies with differences in regional housing stock and space conditioning equipment. This study's results and methodology could be used in future research to compare the cost-effectiveness and carbon reductions of potential weatherization programs.

1. Introduction

A substantial amount of energy is consumed to heat and cool houses. In the U.S., residential buildings account for 22% of primary energy consumption, of which space conditioning (i.e., heating and cooling) accounts for 41% [1]. Weatherization treatments can make houses more energy-efficient, which results not only in reduced energy bills, but also in lower carbon emissions, improved air quality [2], job creation, and increased national security [3]. Following the energy crisis of the early 1970s, the Weatherization Assistance Program (WAP) was created in 1976 to help low-income families lower their energy bills by implementing weatherization measures [4]. Low-income households are not only those that could most benefit from lower energy bills, but they are also typically less energy-efficient: low-income houses are on average 20% more energy intensive than non-low-income houses [5], and analysis of a national leakage database determined that leakage is 145% higher in low-income houses than in non-low-income houses [6].

Since WAP's inception, the program has been appropriated approximately $6.5 billion, with an additional $5 billion granted under the American Recovery and Reinvestment Act of 2009 in order to weatherize almost 600,000 houses [4,7]. Should government support for weatherization assistance (Wx) programs continue, it is advantageous to predict where weatherization programs can save the most energy. Prior studies have noted that the design and performance of conditioning systems [8,9] and houses [6,10] varies regionally. Fig. 1 demonstrates how space conditioning energy use varies substantially among different Census regions and climate zones, while the amount of energy consumed for water heating, lighting, and appliances remains relatively constant [11].

Because space conditioning energy use varies geographically, it can be expected that retrofit effectiveness will vary as well. Measuring the energy savings expected from a retrofit, however, can prove challenging. The empirical method for measuring energy savings consists of comparing a household's energy consumption before and after retrofitting. These comparisons must be

Abbreviations: A, attic insulation; AHS, American Housing Survey; CWP, Conservation Works Program; EIA, Energy Information Administration; GJ, gigajoule; HES, Home Energy Saver; HDD, heating degree day; LBNL, Lawrence Berkeley National Laboratory; MMBTU, Million British Thermal Unit; MSA, metropolitan statistical area; NWAPE, National Weatherization Assistance Program Evaluation; PRISM, Princeton Scorekeeping Method; RECS, Residential Energy Consumption Survey; S, air sealing; T, programmable thermostat; TMY2, typical meteorological year; WAP, Weatherization Assistance Program; Wx, weatherization assistance.

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http://dx.doi.org/10.1016/j.enbuild.2013.11.035

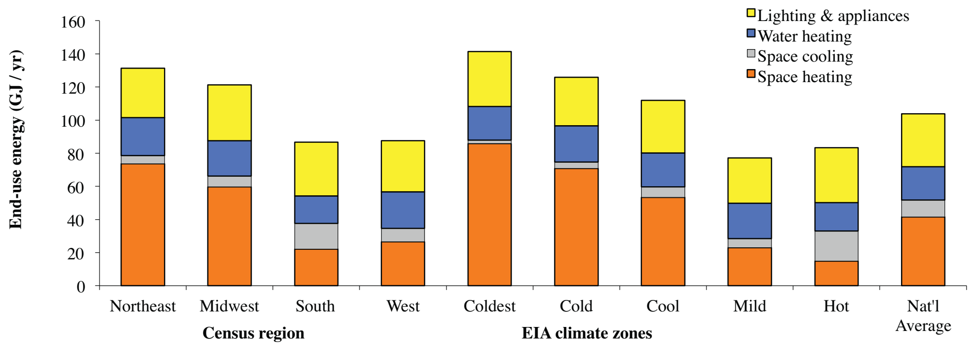

Fig. 1. Delivered energy for an average household by end-use, census region and climate zone.

Data source: [5,11].

normalized for weather conditions, since energy used for space conditioning depends on outside weather conditions. Because of these and other factors, it is standard practice to use an entire year of energy consumption before and after retrofitting in order to determine energy savings. The industry standard for analyzing these data is the Princeton Scorekeeping Method (PRISM), a statistical model that processes weather data and a year of monthly energy bills to produce a weather-normalized measure of energy consumption [12]. The National Weatherization Assistance Program Evaluation (NWAPE), an evaluation of the measured effectiveness of WAP programs across the country, is currently underway, but the results of this evaluation were unavailable at the time of this study's completion [13].

To facilitate energy modeling when sufficient energy bill or weather data are unavailable, many different building energy simulation programs have been developed since the 1980s [14,15]; however calibrating and validating these models is a topic of ongoing research [16–19]. For example, a recent evaluation of several popular residential energy simulation programs found that the mean difference between observed and modeled natural gas consumption ranged from approximately −21% to 36% [20]. Following weatherization treatments, discrepancies between modeled and observed energy consumption are classified as "rebound effects," primarily caused by a combination of shortfall (technical estimation error or improper weatherization treatment installation) and take-back (behavioral energy consumption changes triggered by the increased energy efficiency expected after weatherization treatment) [21–23]. These discrepancies will be empirically accounted for in this study, but their underlying causes and categorizations will not be pursued in depth.

Despite such uncertainty surrounding the quantitative accuracy of energy simulation programs, they are still widely employed by energy auditors as they can still prove to be useful qualitative decision-making tools. This study will use energy modeling software to compare weatherization treatment scenarios for different housing stocks and climates. This method is not intended to replace WAP impact assessments, which empirically measure the energy savings realized in retrofitted buildings (e.g., [24–27]). Rather, the goal of this paper is to develop a method to estimate and compare potential weatherization savings in locations where observational data are unavailable.

2. Data and methodology

2.1. Energy and retrofit modeling

The Home Energy Saver (HES) software was selected for this study to model expected energy consumption and savings gained from retrofitting treatments with publicly available technology. HES is a freely available web-based residential energy audit tool developed and maintained by Lawrence Berkeley National Laboratory (LBNL). HES relies on user input, housing stock statistics, and the building simulation DOE-2 engine to approximate whole house energy consumption, potential energy savings with various retrofit treatments, and the costs of such treatments. HES was selected over other models because it is readily available, comprehensive, and user-friendly. In an evaluation of three top house energy modeling programs – SIMPLE, REM/Rate, and HES – HES was the publically available software that required the fewest data inputs and the least time for data entry [28]. A comparison of the different models is provided in Table 1. This added complexity of the other publically available software, REM/Rate, while potentially useful, can result in larger modeling error if the needed inputs cannot be estimated accurately (such as when a large number of houses are being simulated). Additionally, in a recent evaluation of these three residential energy simulation programs, HES modeled natural gas consumption more accurately than SIMPLE or REM/Rate; the mean difference between observed and modeled natural gas consumption were −9.6% for HES, −21% for SIMPLE, and 36.1% for REM/RATE [20]. Another recent study found that, when building physical characteristics and occupant behavior are accounted for, energy consumption as modeled by HES is accurate to within 1% of actual values when averaged across a group of homes [29]. Finally, we judged HES an appropriate choice for this study given that past McKinsey & Co. analyses [22,30] have used HES to estimate the energy consumption and possible savings from retrofit treatments in the residential sector. Because our study only considers energy consumed for space conditioning, this discussion of HES is limited to those aspects of the model related to space conditioning.

HES calculates and reports end-use energy savings expected for the modeled house with prescribed retrofitting treatments. HES reports these savings both by end-use category (i.e. space heating, space cooling, water heating, appliances, lighting) and by fuel (i.e. gas, fuel oil, or electricity). Space conditioning energy consumption depends on a significant number of factors including, but not limited to: geographic location; house construction and foundation type; appliance use; the quality, quantity, and location of windows; building orientation; HVAC equipment type and efficiency; insulation levels in the floors, walls, and ceilings; air-tightness of the house envelope; and residents' energy-consumption behavior. HES models the major components of space conditioning that Wx programs frequently address: namely, building envelope insulation and air-tightness, HVAC equipment type and efficiency, and residents' energy-consumption behavior [9].

To model these components, HES sends the relevant equipment and house envelope information to DOE-2 software. DOE-2 is a widely used and accepted building simulation program: the U.S. and other countries have developed building standards on the basis of DOE-2, and many design and consulting firms use DOE-2