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Greenhouse gas mitigation benefits and cost-effectiveness of weatherization treatments for low-income, American, urban housing stocks

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ABSTRACT

This paper investigates how greenhouse gas (GHG) mitigation benefits and cost-effectiveness of weatherization treatments vary geographically due to differences in climate, energy production mix, and housing stock. Using a treatment cost database and methods that estimate the residential energy savings from weatherization, we estimated energy cost savings, GHG savings, and measurements of cost-effectiveness. Combinations of three weatherization treatments were modeled: replacing a standard thermostat with a programmable thermostat, installing attic insulation, and envelop air sealing. These treatments were modeled for the low-income housing stock of six contrasting American urban areas: Orlando, Florida; Los Angeles-Long Beach, California; Seattle, Washington; Philadelphia, Pennsylvania; Detroit, Michigan; and Milwaukee, Wisconsin. Results show that (1) regional variations have high impact on the cost-effectiveness of weatherization treatments, (2) housing stocks with substantial electric space conditioning tend to offer greater energy cost and GHG savings, (3) the effect of a GHG price is small compared to energy cost savings when evaluating the cost-effectiveness of weatherization treatments, and (4) installing programmable thermostats is the most cost-effective treatment. This study highlights the importance of thoughtful consideration of weatherization program goals when selecting cities or regions to prioritize because different goals suggest different weatherization strategies.

1. Introduction

Largely inspired by concerns with energy production and climate change, residential energy use is a topic of significant interest, particularly within the fields of engineering and public policy. In the United States (U.S.), the residential building sector is responsible for 21% of primary energy consumption, of which 36% is used for space conditioning (i.e., heating and cooling) [1]. By reducing energy use for space conditioning, weatherization treatments can make buildings more energy-efficient, and, consequently, offer substantial reductions in greenhouse gas emissions (GHGs). In the U.S., residential buildings are responsible for approximately 21% of annual emissions of greenhouse gases (GHGs) [2], and research suggests that retrofitting strategies are more effective at stabilizing GHG emissions compared to other building strategies, such as the construction of net zero houses or other high performance green buildings [3]. Moreover, among the opportunities for energy-efficiency improvements in different sectors, buildings are recognized as the sector in which the potential for efficiency is the largest, least expensive, and requires the shortest lead time to implement [4]. In particular, in the residential sector, space cooling is the end-use with the greatest potential for electricity savings through energy-efficiency measures [5].

In addition to these environmental impacts, residential energy consumption includes a substantial social impact. For low-income households, energy use often represents a significant financial cost; these households pay approximately 14% of their income on energy bills, compared to 3% for other households [6]. Contributing to this burden, compared to middle- and high-income houses, low-income

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Abbreviations: A, attic insulation; ACH50, air changes per hour at 50 Pa; AHS, American Housing Survey; CO2, carbon dioxide; CO2e, carbon dioxide equivalent; EIA, Energy Information Administration; eGRID, Emissions & Generation Resource Integrated Database; GHG, greenhouse gas; GJ, gigajoule; HES, Home Energy Saver; MSA, Metropolitan Statistical Area; NREMD, National Residential Efficiency Measure Database; Pa, pascal; S, air sealing; T, programmable thermostat; U.S., United States; WAP, Weatherization Assistance Program.

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houses are, on average, 20% less energy-efficient [7] and have more than twice as much leakage as [8]. Furthermore, improvements in space conditioning in low-income housing represents 19% of the available energy efficiency gains in the residential sector [9]. With the primary goal of reducing the burden of energy costs on low-income households, the U.S. Department of Energy administers the Weatherization Assistance Program (WAP), which provides grants to improve energy-efficiency in low-income residences. Since its creation in 1976, WAP has helped fund projects to weatherize over 7 million homes across the country, more than one million of which have been completed since 2009, when the American Recovery and Reinvestment Act of 2009 allocated $5 billion for WAP [10]. In addition to reducing annual household energy bills by typically $250–$400 [6,10], these retrofits include several external benefits, namely decreased energy consumption, lower GHG emissions, improved air quality, higher home values, job creation, and enhanced national security [11–14].

While the environmental and social issues associated with residential energy use affect communities across the country, there has been little research into the geographic distribution of potential costs and benefits of weatherization treatments. Readers seeking a detailed literature review of housing retrofit analysis studies at various scales are referred to Hoşgör and Fischbeck [15]; while these studies present various novel methods for measuring or predicting energy use and the effectiveness of retrofits, a limited number of those studies (highlighted below) compare energy savings across regions at the housing stock scale, and fewer detail regional variations in weatherization costs and benefits other than energy conservation. Previous research by the authors has evaluated the energy savings expected from weatherization treatments in six different American cities and confirmed that these savings vary substantially due to differences in climate and housing stock [16]. In particular, that study found that greater energy savings generally existed among housing stock in colder climates; however, it did not assess the costs of these weatherization treatments or any benefits beyond energy savings, which, as discussed above, is just one of several benefits of weatherization. In a study of smart meter data from residences in multiple U.S. states, Kavousian et al. [17] confirmed that weather, house location, and physical building characteristics (namely, floor area) were the most important determinants of electricity use, a portion of which is due to space conditioning. A later Oak Ridge National Laboratory WAP evaluation study supported the conclusion that energy savings were generally greater in colder climates [14,18]; this study also found that weatherization treatments were typically more cost-effective in colder climates, though there is limited discussion about how regional trends in housing stock and energy production mix contribute to this finding. In their studies of Greek housing stock, Droutsa et al. [19] and Balaras et al. [20] evaluated how weatherization treatment costs, energy savings, and GHG savings vary due to differences in building type and climate; these studies did not include an assessment of variations in energy production mix or energy prices within the subject housing stocks.

The purpose of our current study is to help close this knowledge gap by evaluating how costs and additional benefits of weatherization vary among low-income housing stock in American cities. Specifically, this paper compares the costs of completing a weatherization treatment with the benefits associated with reduced energy bills and GHG emissions. Through a comparative analysis of low-income housing stocks in six American cities, this study investigates how the costs and various benefits of weatherization treatments relate to one another and vary due to differences in factors such as climate, physical characteristics of the housing stock, energy prices, and the carbon-intensity of energy sources. A goal of our study is to demonstrate a method that decision-makers can use to evaluate tradeoffs associated with different weatherization program strategies across the country; in particular, they can make more informed decisions about where weatherization treatment programs are the most likely to meet social or environmental objectives, such as reducing energy costs or GHG emissions.

2. Methods

2.1. Review of household data and building energy modeling

This study followed the methods established by Bradshaw et al. [16] to model potential energy savings in low-income, urban housing stock in six American Metropolitan Statistical Areas (MSAs) across a range of climate zones: Orlando, Florida (hot); Los Angeles-Long Beach, California (mild); Seattle, Washington (cool); Philadelphia, Pennsylvania (cool); Detroit, Michigan (cold); and Milwaukee, Wisconsin (coldest). To briefly summarize this approach, American Housing Survey data was used to describe the low-income urban housing stock in these six cities, which represent a range of geographic and climatic areas. These data served as inputs into the Home Energy Saver model, which was used to simulate current energy consumption and the predicted energy savings from a combination of three weatherization treatments: replacing a standard thermostat with a programmable thermostat (T), installing attic insulation (A), and envelope air sealing (S). In addition to these three treatments being the ones modeled by Bradshaw et al. [16], the WAP and other research specifically identify these as three of the most simple and effective weatherization treatments [10,14]. Energy savings are reported by fuel type based on the type of space conditioning equipment in the building; for example, if a residence uses a gas furnace for heating, then the model reports both the gas and electricity savings associated with the heating system. The method was evaluated in the previous study [16] by comparing the simulated savings to observations in Philadelphia; a good agreement was generally found although the model tends to overestimate the savings from combined treatment scenarios. Therefore, no further evaluation of the model's skill in capturing energy savings is conducted in this study. For reference, Fig. 1 shows the average end-use energy savings expected with these weatherization treatments for the six cities. Although this figure is reproduced from Bradshaw et al. [16], it is included in this paper to provide useful context for the current study's results and discussion.

2.2. Costs and benefits of energy savings

Beyond the modeling method established in Bradshaw, Bou-Zeid, and Harris [16], which only examined the energy savings associated with weatherization, our current study considers the costs of these weatherization treatment and how the energy savings result in reduced energy bills and GHG abatement. Prior studies (e.g., [19,20]) of the costs and benefits of residential weatherization retrofits at a large scale applied a national conversion factor to compute the GHGs associated with energy production. Given the geographic variability in the fuel mix used for heating and electricity production, we hypothesize that the cost savings and GHG abatement per unit saved energy will vary significantly. The following subsections describe the methods used to estimate these parameters. To calculate the city-wide average of a parameter, we first calculated the parameters individually for each of the residence types described in our AHS subset of interest (i.e., low-income housing in six cities); these residences were distinguished by whether they were attached or detached, and by their type of foundation, number of floors, vintage, heating equipment, the cooling equipment. Subsequently, in computing the parameter averages and variances, we weighted the results of each modeled