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Energy savings and emissions reductions associated with increased insulation for new homes in the United States

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ABSTRACT

Residential energy efficiency measures can influence air pollutant emissions from power plants and residential combustion sources, with corresponding influences on public health and climate change. However, studies to date have not quantified national-scale benefits using models that account for variability in state housing codes and complexities in energy consumption patterns and electricity markets. In this study, we used the energy simulation software EnergyPlus within a high-performance computing platform to estimate the energy savings associated with increased residential insulation for a cohort of 665,000 new homes built in the United States in 2013. We linked hourly electricity savings with state-specific electricity dispatch models and quantified emissions reductions from power plants and residential combustion sources. We estimated reductions of 180 GWh of electricity and 840 million SCF of natural gas per year, among other combustion fuels, resulting in annual emissions reductions of 470,000 tons of carbon dioxide, 1,100,000 pounds of sulfur dioxide, and 770,000 pounds of nitrogen oxides. Our findings indicate that including the monetary value of health and climate benefits significantly reduces the payback period for energy efficiency investments, and our modeling platform allows for rapid comprehensive analyses of the economic and environmental benefits of alternative energy efficiency measures.

1. Introduction

Residential energy efficiency measures can provide economic benefits to residents, but can also reduce the amount of electricity generated by power plants as well as the amount of direct residential combustion of natural gas, fuel oil, wood, and other feedstock. Such measures have the potential to reduce greenhouse gas (GHG) emissions, emissions of criteria pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NOx), and an array of other pollutants. Within the Clean Power Plan, the United States Environmental Protection Agency (US EPA) has proposed state-specific goals for reducing carbon dioxide (CO_2) emissions from power plants, and states may develop plans that include programs to improve residential energy efficiency [1]. However, CO_2 emissions reductions from residential energy efficiency measures can be challenging to quantify at the state level, given variable code status, differential fuel utilization, and the complexities of evaluating the power plants influenced by marginal reductions in electricity demand. Moreover, it would be valuable for decision-makers to understand criteria pollutant co-benefits related to policy measures targeting CO_2, given the public health implications [2].

Previous studies have addressed dimensions of this question but have yet to capture an integrated picture of energy consumption and emissions reductions related to residential energy efficiency measures on a national scale. Multiple studies have quantified energy and/or economic benefits associated with residential energy efficiency but have not extended the analysis to consider pollutant emissions [3,4]. Older studies quantified the energy, economic, environmental, and health benefits of increasing residential insulation in homes across the US as an example of a specific energy efficiency measure [5–9], but these studies lacked the computational resources necessary to directly model numerous home types

Abbreviations: AVERT, AVoided Emissions and geneRation Tool; CO_2, carbon dioxide; DOE, US Department of Energy; EPA, US Environmental Protection Agency; GHG, greenhouse gas; IECC, International Energy Conservation Code; LPG, liquefied petroleum gas; NOx, nitrogen oxides; $PM_{2.5}$, fine particulate matter; PNNL, Pacific Northwest National Laboratory; RECS, Residential Energy Consumption Survey; SO_2, sulfur dioxide.

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across multiple climates. More recent studies have also limited their scope to a subset of building types or states [10], in part because of the computational burden of modeling numerous homes using energy simulation software. Others have studied commercial energy efficiency measures [11] and have quantified the related air pollution and GHG co-benefits [12] but have not specifically investigated the residential sector.

Moreover, none of these studies fully incorporated the complexity and geographic heterogeneity of the electricity generation sector. Estimating changes in power plant emissions requires insight about the cost of generating electricity on the margin for an array of power plants, as an energy efficiency measure will influence those power plants that generate electricity at the highest price, given the competitive bidding nature of electricity dispatch in the US. This will also vary by time of day and season, as peaking power plants may be influenced on the margin during the hottest hours of the summer, while baseload power plants may be influenced on the margin during times of lower electricity demand. Residential insulation and other energy efficiency measures that primarily influence space heating and cooling will yield electricity savings with strong diurnal and seasonal patterns, so application of a single emissions factor to annual electricity reductions may lead to significant uncertainties.

In this study, we developed a modeling platform that will provide insight at the state and federal level about the energy savings and emissions reductions associated with increased residential insulation, as an example of a specific energy demand reduction effort. We applied the energy simulation model EnergyPlus [13] to residential housing templates representing all new homes built in the US, leveraging high-performance computing capabilities, and quantified the implications by state of changing from current code status to insulation levels consistent with the recommendations in the 2012 International Energy Conservation Code (IECC). We used an electricity dispatch model to quantify the power plant emissions reductions associated with hourly changes in electricity demand by state throughout a calendar year, and we quantified emissions reductions from direct residential combustion. These outputs can provide insight about the economic, climate, and public health benefits of residential energy efficiency measures.

2. Methods

As indicated in Fig. 1, our modeling platform has three major elements: implementation of energy simulation models for templates representing all new homes in the US at baseline and with increased residential insulation; estimation of how many new homes within each state correspond to each template, with the corresponding calculation of energy consumption by state; and calculation of emissions reductions by state for both direct residential combustion and electricity generation. We describe our approach for each of these three model elements below.

2.1. Residential energy modeling

To quantify the energy savings associated with increased residential insulation, we applied the EnergyPlus simulation software used by the Building Energy Codes Program at the US Department of Energy (DOE) and others to quantify building-wide energy consumption [14–16]. EnergyPlus has many desirable features relative to other simulation models [17] and has been extensively applied and validated in the peer-reviewed literature [18–22]. In addition, the Pacific Northwest National Laboratory (PNNL) has developed and made available for use a set of EnergyPlus housing templates intended to represent new housing across the US for multiple editions of the IECC [23]. These templates include four heating system types (electric resistance furnace, natural gas furnace, oil furnace, electric heat pump), four foundation types (slab, crawlspace, heated basement, unheated basement), two home types (single-family detached and low-rise multi-family), 119 climate locations, and the three most recent editions of the IECC (2006, 2009, 2012), for a total of 11,424 templates.

To implement EnergyPlus for our application, we selected the PNNL templates corresponding to the state-level residential energy code status in place as of October 2014 [24], which we used to represent baseline conditions. Ten states (California, Delaware, Illinois, Iowa, Maryland, Massachusetts, Montana, Rhode Island, Virginia, and Washington) and the District of Columbia had adopted the 2012 IECC as of October 2014, so these states are excluded from our analyses of the benefits of increasing insulation levels for new housing to the 2012 IECC. In addition, we excluded Alaska and Hawaii from our analysis, as data were not available to conduct electricity dispatch modeling for these states.

We updated the insulation levels within these baseline templates to reflect 2012 IECC insulation requirements, and calculated the difference in energy consumption between the two templates using EnergyPlus. Because this required us to edit and process thousands of EnergyPlus housing templates, we developed code in Python that allowed us to conduct batch file edits. Python is a high-level programming language that allows for batch processing of files, and the use of Python allowed us to extend previously-developed code in Eppy [25], a Python library for interacting with EnergyPlus input and output files. This process essentially involved extracting the insulation attributes from the 2012 IECC templates and introducing these attributes into the EnergyPlus input files for baseline templates. Similarly, we developed code in Python to run all derived templates (baseline code and 2012 IECC insulation versions of the aforementioned templates) through EnergyPlus and to extract the outputs relevant to our analysis, a process that would be impractical if done manually. All runs were done on the Shared Computing Cluster, a heterogeneous Linux cluster at Boston University. For tasks that were independent (e.g. the batch template file updates), the Python scripts were executed in parallel using the cluster's job scheduler. Subsequently, the collected output files were post-processed using SAS v. 9.3.

We matched corresponding weather files [26] to each template to capture location-specific schedules. Beyond structural attributes, each template also included a series of assumptions regarding activity patterns in the home that would influence energy consumption. For more detail regarding these assumptions and other characteristics of the basic modeling platform, please see Taylor et al. [14]. As in Taylor et al., we assume full code compliance both at baseline and with increases to 2012 IECC. Key outputs included electricity and combustion fuel use for each hour of the year, stratified by usage category (e.g., heating, cooling).

2.2. Estimation of energy consumption by state

To appropriately weigh the outputs from the EnergyPlus template simulations, we needed to estimate the number of new homes built in a given year by state and template type. We estimated the total number of new single-family and multi-family homes by county from 2013 building permit data [27]. For multi-family homes, we only included the buildings that were three stories or lower, which would be subject to the IECC residential provisions. The percentage of homes fitting this attribute was determined by region of the country (Northeast, South, Midwest, West) using 2009–2013 US Census data [28] and was applied to each county within the region.

To determine the percentage of these homes with each of the four foundation types used in the PNNL templates (slab, heated