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Residential energy retrofits in a cooling climate

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ABSTRACT

In this analysis we calculate the effect of energy retrofits in almost 500 homes in Austin, TX. We used measured daily energy use data (kW h/day) from before and after the homes received energy retrofits. These retrofits included attic insulation, new heating, ventilation, and air-conditioning (HVAC) systems, window screen/film, new windows, new ducts, and added duct insulation. We used a mixed effects regression model (with and without interaction terms) to identify the impact of each type of retrofit, as many homes received multiple measures. We used both utility rebates (to the homeowner) and total retrofit cost information to find the levelized avoided cost ($/kW h) of energy consumption to both the rebate issuing entity (in this case, Austin Energy – the local municipally owned electric utility) and the homeowner. Results indicate that, at current rebate levels, all "rebate costs" incurred by the utility are less than the average cost to procure energy on the wholesale market ($0.035/kW h). Thus the utility could make a profit by forgoing energy sales to local residential customers and instead selling into the market. Regression results show that increasing attic insulation, replacing older heating, ventilation, and air-conditioning (HVAC) systems, and replacing duct systems will most likely be cost effective for the homeowner at the current time, i.e. the costs are less than the current electricity rate (about $0.11/kW h), but replacing windows might not.

1. Introduction

Residential buildings are significant users of energy. In the US, residential buildings are responsible for over 20% of primary energy consumption [1] and about 20% of US carbon emissions [2]. Summer wholesale electricity prices are usually driven by residential air-conditioning load in cooling climates such as Texas [3]. However, less than 1% of total research and development investment is spent in the residential sector [4]. This lack of research funds indicates that the residential sector might contain an underinvested opportunity for building energy savings.

Energy efficiency has long been proposed as the lowest-cost option to reducing energy use and greenhouse gas emissions [5,6]. However, most assessments of energy retrofits are based on engineering calculations, but do not use measured data [5]. In this case, engineering calculations predict potential energy savings that might result from technical improvements. However, these calculated potential savings are not always realized. Unfortunately, because of a prior lack of measured data, the reasons for the under-realized energy savings have been hard to pinpoint [7]. Furthermore, using real data is important because sometimes the "rebound effect" can erode some or all of the technically feasible savings [8–12]. Previous studies have examined the empirical effect of retrofits in heating climates [12–16]. However, few studies have presented data-driven results from cooling climates [16,8]. This study looks to fill that knowledge gap by empirically assessing the actual effect of retrofits on energy use for the hot and humid climate of Austin, TX using granular smart meter data.

This analysis used measured daily energy use data from 496 homes before and after they received energy retrofits. These retrofits included attic insulation, new air-conditioning systems, window film, new windows, new ducts, and added duct insulation. Not all homes received the same set of retrofits, and they

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were conducted at different times between 2011 and 2013. Also included in the dataset were the rebate amounts that each home received for each retrofit as well as the final cost associated with the individual retrofits. This financial information allowed the cost per kW h of energy saved to be quantified for the rebate issuing entity (in this case the local electric utility) and the homeowner.

2. Methods

2.1. Datasets used in this analysis

Austin Energy (AE), the municipally owned electric utility for Austin, TX, provided records of energy efficiency retrofits and daily electricity consumption for over 1700 homes whose owners participated in one of AE's residential energy efficiency retrofit rebate program between 2011 and 2013. Other information about the homes included home heating type, year built, home size, the actual USD$ amount of the rebates received for the retrofits, and the total USD$ costs of the retrofits to the homeowner. For homes that installed new HVAC systems, the before and after energy efficiency ratio (EER) values and system capacities were included in the dataset. All homes' attic insulation levels were provided, even if they did not receive an attic insulation retrofit. Most homes upgraded their attic insulation levels to R-38 [RSI-6.7] as the rebate only included incremental insulation increases up to R-38 (RSI-6.7).

Another dataset provided included daily electric meter reads (kW h/day) for the homes before and after their participation in the previously mentioned programs. Only homes with at least 9 months of energy use data (including cooling months: June to August) were included in the analysis. Homes with less than 9 months of usage might not have been able to experience full meteorological differences in Austin. In addition, only homes that utilized natural gas for heating were considered in this analysis. Because we did not have heating information for the homes that use natural gas, we decided to exclude those homes that used electricity for heating for data consistency.

This paper will provide a panel regression analysis of the aforementioned datasets to determine the effect of individual retrofits, pairs of retrofits, as well as analyze the rebates and costs of the retrofits. Fig. 1 shows the layout of the structure of the analysis.

2.2. Creating the panel dataset

The first step of the analysis included curating and merging the two different datasets (daily energy use and retrofit data) to create the panel dataset. The energy retrofits were represented as dummy variables with a 0 if the home had not received the retrofit by that date and a 1 if that home had received that retrofit by that date. The only exception being for attic insulation levels, which are represented as a continuous variable across all the homes. For example, if a home received a new HVAC system on 2011-09-05, the value for HVAC would be 0 for that home prior to 2011-09-05, and 1 after 2011-09-05. The dates of retrofits varied by homes as did the number of measures for each home. Consistent with NREL's Whole-Building Retrofit with Consumption Data Analysis Evaluation Protocol [17], cooling degree days (CDD), with base=67°F (19.4 °C), and heating degree days (HDD), with base=65°F (18.3 °C), were also paired with the dates to account for weather driven effects. To insure data consistency, homes that had extended periods of zero usage, changed ownership during the time period considered, or that had an average log daily use that was greater than 2 standard deviations away from the mean were removed from the dataset. The final dataset included 496 homes. Table 1 gives a statistical breakdown of the homes' continuous explanatory values.

There was considerable overlap in some of the retrofits as many homes received a suite of them based on their needs. Homes that participated in the program typically received more than one retrofit recommendation. Table 2 shows the relationship between pairs of retrofits.

The bold diagonals of Table 2 indicate how many individual homes received that retrofit and the off diagonals indicate how many homes received both retrofits – *HVAC* means that the home received a new HVAC system, *ATTIC* indicates that the home upgraded their attic insulation, *FILM* means that a low-E coating was applied to the home's windows, *WINDOW* means that the home got new windows, *DUCT* means that the home got a new duct system, and *DRAPE* is a retrofit where the ducts that run through the attic are covered in loose fill insulation.

2.3. Costs and rebates of the energy retrofits

Table 3 gives a statistical summary of the retrofit costs and rebates. The rebate values are the actual rebates provided by Austin Energy to customers that went through one of their energy retrofit programs. The costs values are the actual final amount that the residential customers were charged by contractors for completing the retrofits. The retrofits had to be completed by one of an approved set of contractors and could not be performed by the homeowner themselves.

2.4. Determining the model and model structure

To account for the assumption of independence, we used a mixed-effects regression model that could accommodate both the random and fixed effects [18], as seen by the following equation:

$$\log(y_{i,t}) = \beta_0 + \beta_1 CDD_t + \beta_2 HDD_t + \sum_{j=3}^{4} \beta_j X_i^S + \sum_{j=5}^{10} \beta_j X_{i,t}^R + \sum_{j=11}^{13} \beta_j X_{i,t}^I + \beta_{14} R_i + e_{i,t} \quad (1)$$

where $\log(y_{i,t})$ is the natural log of the amount of energy (kW h) consumed by home i on day t, $\beta_{1:13}$ are the fixed effects regression coefficients, X_i^S is the set of home structural fixed effects explanatory variables such as home age and size, $X_{i,t}^R$ is the set of possible retrofit fixed effects explanatory variables, $X_{i,t}^I$ is the set of possible retrofit interaction term fixed effects explanatory variables, β_{14} is the vector of coefficient estimates for random effects, R_i is a list of house identification numbers [19], and e_{it} is the error term. This model is similar to that used in current M&V protocols [17,20]. The Interclass Correlation (ICC) value was calculated to determine the appropriateness of the mixed model.[1] Since the predicted value is the log of electricity use, Eq. (3) gives the percent change in daily energy use associated with either the home characteristics or the retrofits $(\beta_{1:13})$:

$$P_{rc} = (\exp(\beta_{rc}) - 1) \times 100 \quad (3)$$

where P_{rc} is the % change in daily energy use resulting from the regression coefficient β_{rc} which is in the set of β's from Eq. (1).

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[1] The Intra-Class Correlation (ICC) is estimated using the following equation:

$$ICC = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \sigma_\epsilon^2} \quad (2)$$

where σ_α is the standard deviation of the homes' random effects and σ_ϵ is the standard deviation of the residuals of the house.