Energy Bill Breakdown: Regional Temperature Variations and Construction Age on Energy Consumption

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ABSTRACT

With the need to reduce greenhouse gas emissions and the fact that 50% of US residential energy consumption is attributable to space heating and air conditioning, it is imperative to understand the variables that influence the use of these technologies. This study analyzes the Residential Energy Consumption Survey of 1,172 samples from the four largest US states- California, Florida, New York and Texas- to determine the relative effects of building age and regional temperature variations on building heating and cooling. Backwards stepwise regression was used to isolate the influential variables in the survey and to build two models, one for air conditioning and one for space heating. Degree Day, building age, square footage, and number of windows were found to be influential on space heating whereas degree day, square footage, number of windows and number of residents were found to be influential on air conditioning. From this model, lmg analysis for relative importance on the heating model revealed that degree day was the most important variable, followed by building age. On the state level, all of the national heating model variables were statistically significant in California and Texas, but not in New York and Florida. Overall, the influence of temperature was found to be the most significant influence on energy consumption for both air conditioning and space heating; however, building codes that focus on building age may still provide valuable energy savings for space heating energy consumption.

KEYWORDS

space heating, air conditioning, building age, degree day, backwards stepwise regression

INTRODUCTION

With the looming threat of climate change, energy consumption in the United States has become increasingly scrutinized for its high amounts of greenhouse gas emissions. With less than 5% of the world's population (Population Division, 2010), the US consumes more than 20% of the world's energy (US EIA, 2009). While it has been predicted that declines in population growth will help to curtail energy consumption (York, 2006), efforts to further reduce consumption may help to decrease the net effects of climate change. Therefore it is important to identify the areas of most waste. Of the total energy consumption in the US, over 20% can be attributed to the residential sector (US EIA, 2010), making energy interventions in the residential home a leading solution to combat US energy over-consumption (Hirst & Moyers, 1973).

The highest contributing factors to residential energy consumption are space heating and air conditioning. Nationwide, approximately 40% of household energy consumption is attributed solely to heating through different fuel sources (RECS table US12, 2008); and in other countries such as Great Britain, this percentage averages as high as 58% (Meier & Rehdanz, 2010). In addition, air conditioning absorbs another 10% of US residential energy consumption (Barry, 2010). Energy consumption from space heating and air conditioning is influenced by a wide variety of factors including geographic, structural, and demographic characteristics (Haas, Auer & Biermayr, 2010). All of these factors are observed in the results of the Residential Energy Consumption Survey, which collects information on over 4,000 households across the United States, as well as, information on building characteristics, appliance use and fuel consumption (Barry, 2010).

The construction age of buildings and regional temperature are two influential variables of space conditioning that represent aspects of the built environment as well as the natural environment of a home. The impact of weather is measured in degree days at the location of the home. These degree days represent the amount of energy needed to artificially increase or decrease the interior temperature of a building to reach a standard temperature (Bonhomme, 2000). While the geographic region of a building may have an obvious impact on energy consumption due to weather variations (Strout, 1961), other factors are not always as intuitive. Climate and weather can easily be observed and tested to determine impact; however, other factors such as building age might be just as statistically influential, but are often overlooked.

Due to factors such as poor insulation and aged heating systems (Chwieduk, 2003), older buildings tend to be less efficient with space heating (RECS Table SH8, 2008) and air conditioning (RECS Table SH12, 2008). While research has been conducted on the broader influences of energy consumption in the household (Rehdanz, 2007), little research has focused directly on weather and building age. Though very different and seemingly unrelated, weather and building age might provide valuable information for policy makers and building designers trying to find a solution to the energy consumption problem.

This study investigates the effects of both regional climates and building age on the amount of energy consumed for space heating and air conditioning in residential homes of the four most populated states: California, New York, Texas, and Florida. I expect to find that the age of buildings will have a statistically significant impact on energy consumption for both space heating and air conditioning. Such a conclusion would render arguments invalid that suggest that weather and temperature are the sole reason for increased consumption in areas that have colder seasons. I hypothesize that the building age and degree days will be significant influences on energy consumption for heating and air conditioning in residential homes, but will have varying importance between states.

METHODS

Study System and Data Collection

For this analysis, I used the energy consumption data for the four most populated states from the Residential Energy Consumption Survey conducted in 2005. These four states include Texas, California, New York and Florida, representing roughly 33% of the US population. Each represents different physical regions and climates in the country. The survey includes 4,382 samples with 1,172 from the four most populated states, and is intended to represent average energy consumption factors for all American households.

Influential Variables

The consumption of energy for space heating and air conditioning is heavily dependent on many factors including structural components of the house, demographic characteristics of the inhabitants and the temperature trends of its location. The structural factors in the model include building age, square footage heated or cooled, the number of windows, the age of the heating and cooling unit, the estimated level of insulation, and whether the air conditioner was energy efficient. The demographic variables in the model include number of inhabitants and average income of household. The geographic variable included in the model is degree days, to incorporate the impact of weather. These variables were chosen based on extensive literature review and the limitations of the survey data.

Building the Model

To test the efficiency of the buildings, I constructed two models with the above factors and statistically determined the relative importance of building age and degree days within the model. The models were created using a backwards stepwise regression technique (Conesa & Nueda, 2005). Starting with nine variables for heating and ten variables for air conditioning, *R Commander* was used to run a linear regression to determine significance (R Development Core Team 2009; Fox et al. 2009). Variables found to be insignificant were removed one at a time until only influential variables remained in the models. The results of the final linear regressions provided the R^2 and coefficients for the variables in the equations.

Statistical Interpretation of the Model

After running the models, I statistically analyzed all of the data to determine the relative influence of each of the factors tested. Using the relaimpo analysis in *R Commander*, the Linderman, Merenda, and Gold method, lmg, provided the relative importance of each variable in both models (Lindeman, Merenda, & Gold, 1980). Relative importance was measured using the percentage of variance contributed by each variable (Gromping, 2006). I implemented this method on both of the models. The results of my relaimpo analysis allowed for ranking of the influential variables.

Next, I ran the model with the data in each of the large states to determine variations across the nation. A linear regression was run using the remaining significant variables and a lmg relative importance analysis was run on the model. The output of this analysis revealed the importance of each variable on an individual state basis.

RESULTS

Energy Consumption Model Results

My backwards stepwise regression produced models that each contained four significant variables with the remainder of the variables found to be insignificant. The model for space heating and air conditioning are below.

Space Heating

BTU's= (0.004) Hot Degree Day+ (0.002) Heated SQFT + (0.183) # of Windows- (0.078)Building Age +164.3

Air Conditioning

BTU's= (0.005) Cold Degree Day+ (0.002) Cooled SQFT+ (0.463) # of Residents+ (0.072) # of Windows +4.78

The linear regression results for the heating model are as follows: R^2= 0.579, F(387.9, 1,127), p<2.2e-16. The p- values of all of these variables were significant (Table 1). The remaining variables were insignificant to the model and were removed.

Table 1. P-Values of Heating Variables. All variables in the table have significant p-values.

Variable	p-Value
Hot Degree Day	<2e-16
Heated Sq ft	3.57e-10
# of Windows	3.00e-7
Building Age	1.12e-11

The linear regression results for the air conditioning model were as follows, R2= 0.684, F(474.9, 877), p<2.2e-16. The p-values of all of the remaining variables were significant (Table 2). Building age was not a significant variable (p-value = 0.89) for air conditioning and therefore it was removed in the third step of the backwards regression.

Table 2. P-Values of Air Conditioning Variables. All four variables have significant p-values.

Variable	P-values
Cold Degree Day	<2e-16
#of Residents	3.9e-6
Cooled Sq ft	<2e-16
# of Windows	0.001

Relative Importance

The relaimpo analysis of the heating model produced the percent variance attributable to each significant variable. For heating, I found hot degree days to be the most important variable, with building age being second most important (Table 3).

Table 3. Relative Importance output for Heating. Degree day is the most important variable impacting the model, while number of windows is the least.

Variable	Percent of Variance
Hot Degree Day	45.2
Building Age	5.9
Heated Sq ft	4.1
# of Windows	2.7

For air conditioning, the lmg values for relative importance revealed that cold degree days was the most important influence on the model and cooled square footage was the second most important variable (Table 4). As stated above, building age was not significant and therefore was not responsible for any percent of the variance in the model.

Table 4. Relative Importance output for Air Conditioning. Degree day is the most important variable impacting the model, while number of residents is the least.

Variable	Percent of Variance
Cold Degree Day	47.5
Cooled Sq ft	17.6
# of Windows	2.3
# of Residents	1.0

Heating by State

Because the heating model included both building age and degree days, I ran this model for each of the large state individually. The model for air conditioning was not run on the state level because building age was not significant in this model. The linear regression outputs for each state are below in Table 5.

Table 5. Linear Regression outputs for State Models.

State	R^2	F	P-value
California	0.33	54.8, 441	<2.2e-16
Florida	0.22	11.7, 171	2.0e-8
New York	0.14	10.1, 244	1.4e-7
Texas	0.25	21.4, 256	3.1e-15

In the California and Texas models, all of the four variables were significant. In the Florida model I found building age and number of windows to be insignificant. In the New York model I found degree day and heated square footage to be statistically insignificant. The results of the relative importance revealed the influence of each variable on the state level (Table 6). I found degree day to be the most important variable in all the models in which it was significant. In those same models, building age was found to be the least important variable in examining the model variance.

Table 6. Relative Importance on the State Level. In all states, except for New York, degree day is the most importance variable.

State	Most Important	2nd Important	3rd Important	Least Important
California	Degree Day	Heated Sq ft	# of Windows	Building Age
Florida	Degree Day	Heated Sq ft	# of Windows	Building Age
New York	Heated Sq ft	Building Age	# of Windows	Degree Day
Texas	Degree Day	Heated Sq ft	# of Windows	Building Age

DISCUSSION

Key Findings

On average, regional temperature and building age were found to be statistically significant for space heating, providing justification for reevaluating building standards; however, building age did not have a significant influence on air conditioning. Degree days was found to be more influential than construction age, but both variables were contributing factors for space heating, indicating that one cannot make the easy assumption that regional temperature is the sole factor dictating energy consumption.

Regional Temperature

The relative importance lmg coefficient of the degree day variable shows that it is the most influential variable in our model; however, humans have little control over this variable except when deciding upon a site for construction. This information is important to my model, but offers little guidance on how to change building codes, besides regional changes to insulation standards. Studies on tree shading (McPherson, Herrington, & Heisler, 1988) correspond well with these findings because they focus on solutions to temperature problems. Degree Days were influential in all states; however, the limited influence in New York may be attributed to building style. Densely populated areas with connected buildings have less heat loss than separated buildings (Wiren, 1983). Meanwhile, all four variables were significant in California and Texas most likely due to their large geographical area and population distribution. For example, California has wide climactic variation (LaDochy, Medina, & Patzert, 2007), and population distribution throughout the state (Figure 1) providing for a variety of conditions that might be representative of the whole country. Overall, the significance of the regional temperature provides further support of building thermal simulation research by Lomas and Eppel (1997), degree day modeling by Quayle and Diaz (1980), and supports common understanding of the effects of weather on space conditioning.

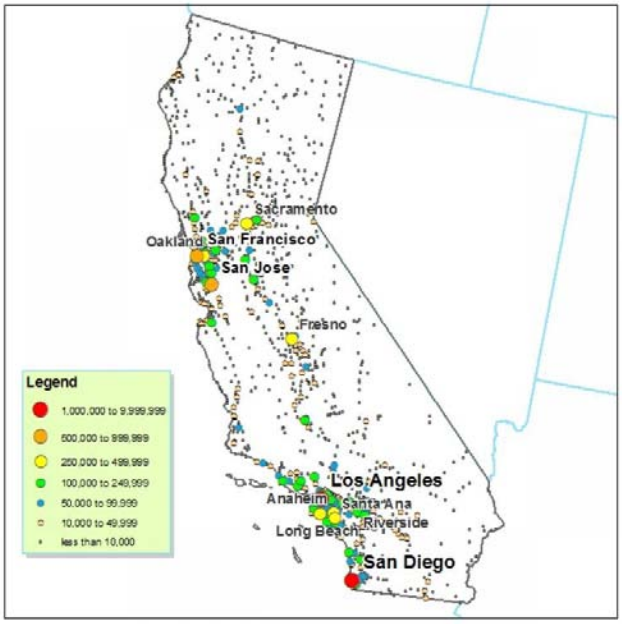

Figure 1: California population distribution by cities. Cities are dispersed throughout the state (California Maps, 2011).

Building Age

While having a lower lmg coefficient than degree days and being insignificant in the air conditioning model, building age was still found to be an influential factor and indicator of building thermal quality for space heating. For this reason, building age cannot be ignored and should be taken into consideration in building codes. Changes to the codes could include reevaluation after a set number of years and mandatory upgrades to prevent unnecessary energy waste (Roberts, 2008). Unfortunately, the building age variable correlates with other variables such as insulation level and equipment age and therefore it's influence might have been skewed in the model building process. With more information on these confounding variables, better models may reveal that building age is actually an influential variable in determining air conditioning energy consumption. However, since the variable of building age does encompass the other variables, it may serve as the best indicator of efficiency, making for an easy estimation in situ. All of the states, except for Florida, showed consistent relationships between building age and consumption, which contradicted my expected result that it would be significant in all states. Since New York has a higher percentage of older buildings from its earlier population booms (Rosenwaike, 1972), it makes sense that building age is more influential in this state, than in the other three. Besides Florida, the consistency between geographic regions provides justification for more universal building codes that focus on building upgrades based on buildings age.

Relative Importance of Variables

The relative importance analysis comparing temperature and building age does not support my hypothesis because it is not influential in space heating, but it does provide support for further research and policy making. The high significance of regional temperature supports the work of White and Reichmuth (1996) and their usage of average monthly temperatures to model energy consumption. Since temperature is the underlying reason for heating and air conditioning, it makes sense that regional temperature was more influential. Due to this fact, the hypothesis for this study might have been too bold to assume that the built environment was just as influential as the surrounding natural environment.

Limitations

Although this study drew from a great deal of data, it was limited by the information collected in the RECS and time allotted for the study. The RECS covers all types of energy consumption in buildings, not just heating and cooling, therefore it includes variables extrinsic to this study and lacks other variables that may provide more insight to the model. Heating and cooling are impacted by other variables of weather, not solely temperature, so it would have been beneficial to have wind, rain, and snow measurements in the study. As found in Simpson and Macpherson's work (1997), shade from vegetation also greatly impacts energy consumption and better measurements would provide further clarity in the model. Since GPS coordinates were not included in the survey, only census regions, it was not possible to retrieve data for these weather variables from other surveys. The length of the study was also a limiting factor because it allowed for the creation of only one model for all six survey years. Only one model was created using the 2005 data. All the same variables may be the same over the years, but unique models for each year of data may have increased the accuracy slightly. Overall, these limitations do not hinder the specific goal of the study, but could be eliminated in future work to provide more robust results.

Future Research

Examining the factors that are influenced by building age, such as insulation levels, crawl spaces, and HVAC equipment, could shed further light on the importance of building age as an overarching variable. In addition, work with more weather data, such as wind, snow pack, and rain, could provide more accurate models demonstrating the interaction between the natural and built environment. More concentrated research on weather data and structural components of buildings could justify and defend the impact of building age and regional temperature on energy consumption.

CONCLUSIONS

This study of residential energy consumption provides an important basis for the field of building science and demonstrates the ability of humans to influence energy consumption based on qualities of their built structures. The model produced in this study provides justification for future research focusing on weather data and thermal quality factors in building, which might hold the key to energy consumption and reducing greenhouse gas emissions (Tuohy, Roaf, Nicol, Humphreys, & Boerstra, 2010). The relaimpo analysis shows the importance of the built environment, but also how it interacts with the surrounding natural world. It shows that while humans can manipulate nature to a certain extent, natural forces may have more influence and humans must learn to adapt. This study, combined with other building science research could provide enough evidence to improve building code requirements throughout various states in order to reduce overall energy consumption in one of the highest consuming sectors.

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