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Modeling Space Heating Demand in Massachusetts' Housing Stock and the Implications for Climate Change Mitigation Policy

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MODELING SPACE HEATING DEMAND IN MASSACHUSETTS' HOUSING STOCK AND THE IMPLICATIONS FOR CLIMATE CHANGE MITIGATION POLICY

A Thesis Presented

By:

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Without my family I would not be the person I am today. Many thanks to Mom, Dad, Emily, Mavis, Adam, and PJ.

ABSTRACT

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This research examines variation in average household energy consumption for space heating in municipalities in Massachusetts in order to understand the magnitude of variation among communities and the potential causes of variation. Residential natural gas consumption data for a sample of communities in Massachusetts was obtained for the analysis. Based upon this data, a regression model is developed to determine building and household occupancy characteristics that influence household energy consumption. The findings suggest dwelling size, tenure, and building age influence household energy consumption.

Based upon these findings, recommendations are developed for the restructuring of federal and state level energy efficiency programs.

Key Words: "Energy Efficiency" "Space Heating" "Split Incentive" "Climate Change Planning" "Household Energy Consumption" "Energy Policy"

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CHAPTER 1

INTRODUCTION

Across the globe, cities and municipalities are beginning to recognize their role in addressing climate change. (Wheeler, 2008). While climate change is a global problem, local governments are becoming more involved in addressing this critical issue. Many city, county and state governments have integrated climate change planning into existing government plans or have created new policy frameworks for addressing climate change more specifically (Hamin and Gurran, 2009). Planning for climate change generally reflects two distinct, yet not mutually exclusive approaches: mitigation and adaptation (2009). Mitigation reflects the necessity to reduce greenhouse gas (GHG) emissions significantly in order to minimize the severity of climate change, while adaptation reflects the need for communities to retrofit the built environment to better sustain shocks caused by increasingly unreliable weather patterns (2009). This research will focus specifically on climate change mitigation through reductions in end-user demand, i.e. curbing energy use derived from carbon intensive fuels.

Planning for climate change is in its relative infancy. Existing research on the subject includes qualitative assessments of planning documents to help clarify what constitutes a climate change plan, while other research has focused more specifically on mitigation and evaluating the effectiveness of climate change plans with respect to meeting goals and benchmarks for greenhouse gas reductions. According to research by Stephen Wheeler (2008) on first generation climate change plans developed by cities, many are not implemented or enforced by local governments. Another shortcoming of these plans is that they consist of policies that are not tailored to a community's individual GHG emissions. With respect to mitigation, they often provide very general goals and objectives that lack the technical substance to actually meet the benchmarks necessary to truly reduce GHG inputs at the local level (2008). This is largely the result of the complexities associated with quantifying emissions sources at local levels of government and geography and being able to pinpoint specific mitigation strategies. Perhaps most importantly, in the absence of comprehensive federal legislation mandating the reduction of GHG emissions, there is little accountability for communities that fail to act.

One possible way to bridge the information gap between national datasets and local inventories is for states to be more involved in climate change planning. In 2009 Massachusetts completed a greenhouse gas inventory in accordance with the requirements of the state's Global Warming Solutions Act, which became law in 2008. The report included a baseline emissions inventory based upon 1990 levels and business as usual projections for the state by 2020. The report is intended to guide and inform decision makers about the scale of the intervention needed to reduce GHG emission levels to 10-25% below 1990 levels by 2020. The report provides an overview of emissions from different sectors, and shows the residential sector[1] accounts for approximately 17% of overall emissions. These emissions are largely associated with the use of oil and natural gas to meet household demand for space and water heating. These findings are not surprising given the climatic conditions in New England, and in the context of reducing GHG emissions across the state, this sector could have significant potential for mitigation (*Massachusetts Department of Environmental Protection* 2009).

The statewide greenhouse gas inventory represents an important first step in documenting baseline conditions to help policymakers in developing meaningful mitigation strategies, however the aggregate data does little to inform municipal level policies and programs aimed at the same result. In Massachusetts, little is known about municipal level emissions and how they vary across communities. There is no research that compares GHG emissions across a range of communities in order to determine if some communities have greater emission levels per measurable unit, e.g. household or capita. Furthermore, determining the causes of variation is extremely important in crafting policies and strategies that can be addressed by municipalities and administered at the local level.

The primary goal of this research is to explore average household energy consumption for space heating to determine if variation exists among municipalities and if so what variables influence this variation. The hope is that

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[1]The emissions associated with residential use only accounts for direct emissions, mainly from space and water heating, and does not include the emissions associated with electricity generation, which in this report are accounted on the 'supply' side.

this information will be useful to policy makers, urban planners, and program administers as they consider strategies to reduce energy consumption in residential buildings.

The research method is a comparative analysis of selected municipalities in Massachusetts to determine if average household energy consumption for space heating varies among municipalities. A regression model is then developed to identify variables that influence this consumption. The research hypothesis is that variation will exist among municipalities' in average household energy consumption based upon measurable independent variables. The variables thought to be most influential to this variation are building age and tenure (owner versus renter occupied). The independent variables of primary concern to this research are building age, renter versus owner occupancy, housing type, and percent of households with a resident over 65 years old. Based upon the results of model, policy implications for federal, state and local mitigation strategies are discussed.

CHAPTER 2

LITERATURE REVIEW

The literature review provides a broad overview of the role of planners in addressing climate change and previous research that informed the development of the research questions and methodology.

I begin by providing a broad overview of the scale of the climate change problem while highlighting the role local governments and planners must play in reducing greenhouse gas emissions. I then review the methods used for quantifying residential energy consumption at various geographic scales, in an effort to understand how baseline inventories for greenhouse gas emissions have been traditionally measured. I then examine the literature that addresses the relationship between urban morphology and household energy consumption in an effort to understand the characteristics of the built environment that influence energy consumption. The focus is further narrowed as I examine the factors influencing energy demand for space heating in residential buildings. This component of the literature review informs the selection of the independent variables used in the model for this research.

2.1 Local GHG Emission Inventories

While climate change is internationally accepted as a critically important issue with benchmarks and thresholds in place to measure global progress towards mitigation goals, many of the decisions that directly affect GHG emissions are rooted in state, regional and local government policy (Crane, 2010, Dodman, 2009). Worldwide, approximately 38% of GHG emissions can be attributed to energy use from residential and commercial buildings, and transportation; both areas where the planner, through land use and transportation planning and improved building codes and energy efficiency retrofits, could potentially play a significant impact in reducing energy consumption and curbing emissions (Crane, 2010). The role of local government in addressing climate change is underscored by the Climate Protection Agreement, which was adopted by the United States Conference of Mayors in 2005. This non-binding agreement aims to reduce GHG emissions to 7% below 1990 levels by 2012 (Sears et al. 2010).

As the role state and local governments play in addressing climate change has emerged, methods for measuring GHG emissions at the state, county and municipal levels have been developed to support decision-makers. Local Governments for Sustainability (ICLEI) is the leading climate change resource for municipalities and local governments within and outside the United States. ICLEI provides a framework, and a software tool, which allows participating communities to inventory existing emissions and set emission reduction goals. The ICLEI method is a 5-step process that includes (ICLEI, 2009):

- Calculating and creating a baseline emission inventory
- Adopting Reduction Goals
- Developing Mitigation Policies
- Implementation
- Monitoring of Results

The ICLEI method is used to inventory emissions from municipal operations, as well as community-wide emissions. This method uses fossil fuel derived energy consumption as a measurement for greenhouse gas emissions. A key component of the methodology is to classify emissions based upon the contributing sector. This provides decision-makers with more detailed information about the source of local emissions and informs appropriate policy and programmatic recommendations. ICLEI classifies the sectors for community scale emissions into seven broad categories, consistent with the IPCC's methodology (ICLEI 2009, Dodman, 2009):

- Stationary Energy (residential, commercial, industrial)
- Transport
- Fugitive Emissions
- Industrial Processes
- Agriculture
- Land Use, Land Use Change
- Waste

The quality of the emissions inventory is directly related to the data that is available from each sector. The ICLEI method includes guidelines on how data should be classified in the inventory, based upon the accuracy of the data, and how representative it is of the specific community. This is an important caveat, as data availability and accuracy, represent two of the most significant challenges to municipalities as they perform GHG emission inventories (ICLEI,2009, Sears et al. 2010).

While GHG inventories are a critical component of climate change mitigation plans, recent research suggests they do not necessarily translate to adequate mitigation policies (Wheeler 2008). Sears et al. performed a detailed review of 30 climate change mitigation plans, which were largely based upon the ICLEI method or a similar approach and found most did not meet mitigation targets through proposed recommendations. The research also found many plans did not address how mitigation measures would lead to emission reductions. The researchers found that one-third of the plans did not include any quantification of emission reductions to be achieved from the prescribed mitigation action, and of the plans that did include estimations, 57% did not include any information on the underlying assumptions that formed the basis for calculations (Sears et al. 2010) This lack of information significantly marginalizes the ability of municipalities to implement plans that meet desired outcomes.

While this research does not focus specifically on climate change mitigation plans, it seeks to improve the knowledge base that informs these plans. The shortcomings of these plans, as detailed by Sears et al. and Wheeler, illustrates why more detailed information about data inputs is needed. My research aims to improve this knowledge base by looking at how variation in residential energy consumption for space heating could impact climate change mitigation policy.

2.2 Urban Morphology and Energy Use

A critical component of this research is to understand how urban morphology and other characteristics of the built environment, influence energy use from the residential and transportation sector. Research suggests that some forms of settlement pattern are less energy intensive, than others. This section will provide an overview of this research to help us better understand how variation in energy use is based upon characteristics of the built environment.

While climate change planning is a relatively new area of study, research connecting GHG emissions and the built environment, whether implicit or explicit, is not new to the field of planning. For the better part of the last 40 years, planners have recognized the connection between land use and energy consumption (Ewing et al. 2008). Although energy use and GHG emissions were not always the evaluative metrics, social critics before and after World War II, such as William Whyte and Lewis Mumford, denounced the inefficiency of "sprawling" development that eats up open space, segregates land use and promotes automobile dependence (Mumford 1961, Whyte 1968).

In recent years, research has emerged that aims to better understand the relationship between urban morphology and energy consumption. By looking specifically at “end user” emissions, the research examines how characteristics of the built environment influence energy consumption from the residential and transportation sectors specifically. Clinton Andrews examined energy consumption along a rural-urban gradient to understand the relationship between energy consumption and land use. The findings of the research suggest that post-World War II suburbs, with their dependency on the automobile, large single-family dwellings, and lack of forested areas to act as carbon sinks, are the most energy intensive type of land use, with respect to residential and transportation related land use. Andrews also found that areas with particularly high density, with smaller dwelling units, and access to public transportation, were the most efficient with respect to emissions (Andrews, 2008). Research by Brown and Southworth (2008) echo Andrew’s findings of variation in energy consumption based upon urban morphology. Their assessment of 100 metropolitan areas found an inverse correlation between energy consumption and density. As density increased, energy consumption decreased as dwelling units are smaller and more compact, and there is more reliance on public transportation (2008).

While the two previous studies looked at variation across distinctly different urban structures and broad geographies, a study of ‘*neighborhood metabolism*’ within Toronto examines variation at a much smaller scale

(VandeWege and Kennedy 2008). This research included an examination of energy demand for housing and transportation, and found variation in GHG emissions among neighborhoods with different building types, density, and access to public transportation (2008). This research shows a direct relationship between the form of the built environment and associative GHG emissions and highlights the importance of recognizing differences in these urban structures when crafting meaningful policies to reduce energy consumption.

The variation in energy consumption as it relates to urban morphology has emboldened many planners and other policymakers at the regional and state levels to implement policies aimed at increasing density, mixing land uses, and providing more and greater access to public transportation. While these are noble goals, there are several shortcomings with focusing on these policies as realistic tools for reducing GHG emissions. On one hand, policies and regulatory frameworks at the federal, state and local government level need to fundamentally shift to encourage land use decisions that significantly reduce "end-user" demand for energy. Secondly, even if a fundamental shift in policy were to occur, it would still take several years to shift the structure of the built environment in a way that decreases energy use from end user demand. In the context of climate change, where scientists suggest drastic steps must be taken immediately, time is of the essence.

One area where climate change scientists and other policymakers believe we could make significant efficiency improvements in the short terms is in residential energy consumption, through both electricity and fuel consumption (Brown and Southworth, 2005). The next portion of the literature review will examine residential energy consumption in buildings to examine if, and why, variation occurs.

2.3 Energy Use In Residential Buildings

Understanding the basic factors that influence energy consumption in residential buildings is critical to the development of the regression model, and the underlying assumptions of the research questions. Research into building energy consumption historically used two distinct modeling techniques: bottom up models that focus on measuring energy consumption in specific buildings and then extrapolate the findings to larger population, and top-down models, which use aggregate datasets to make generalizations about a larger population of buildings (Swan and Ugursal).

2.3.1 Household Energy Consumption Modeling Techniques

There is a growing body of literature that aims to explore energy consumption in buildings and the factors influencing consumption. A survey of research approaches by Swan and Ugursal (2009), and another done by Kavigic et al. (2010) provide rather comprehensive overviews of the modeling techniques used for measuring residential energy consumption. The methodologies provide different approaches, which are based upon expertise and scholarly discipline, as well as data availability (Ugursal and Swan, 2009). Swan and Ugursal's review separates methodologies into two distinct approaches, top-down and bottom-up. The top-down method uses highly aggregate energy data and variables (GDP, employment, housing age) to measure energy consumption at large spatial scales. Top-down approaches do not differentiate energy demand across different end-uses, making it difficult to distinguish potential mitigation alternatives or differences in energy use across a population. Generally, the top-down approaches are most typically used to compare how energy use has changed over time at a specific geography (Kavigic et al. 2010). The benefit of top-down approaches is the relative ease with which they are developed, making historic benchmarking and comparisons by country, relatively straightforward. The weakness of the top-down method, which is particularly relevant to this research, is they lack detailed data inputs, and the large scale at which energy demand is measured, makes it nearly impossible to distinguish the cause of variation among the data. This '*wash-out*' factor makes these models largely inadequate for policymakers interested in addressing more specific local issues (2010).

The bottom-up methodology utilizes more disaggregated data to create models that explain energy consumption as a function of key independent variables that are typically physical characteristics of the building (Swan and Ugursal 2009). The most widely used of the bottom-up models are typically associated with physics and engineering disciplines. These models measure the thermal qualities of individual building components—roof, floor, and walls— by assigning an energy loss coefficient to each. The strength of this approach is that by isolating individual components of a building as a function of energy loss, it allows policymakers to better predict the effectiveness of building retrofits on energy savings (Kavigic et al. 2009). These building features can then be classified according to a time-period in which the building was constructed, which broadens the applicability of the research to a larger population (Huang and Broderick, 1999).

In the United States, Huang and Broderick (1999) developed a detailed bottom-up model of building typologies correlated to energy use, which filled a research gap by allowing policymakers to better understand the energy savings associated with specific buildings and individual building retrofits. The study classified buildings by age, building type, and region, and used computer simulation to measure the building characteristics as a function of an energy loss coefficient. In all, 45 single-family prototypes and 16 multi-family prototypes were tested across 16 regions of the United States, including Boston. The key finding of this research is that as buildings age, they experience more heat loss (1999).

2.3.2 Building Characteristics and Energy Consumption

Beyond Swan and Ugursal's review of modeling techniques for residential energy demand, there is a significant body of research that has explored the relationship between building age and energy use. This research, which has largely taken place in Europe, has established a correlation between building age and energy demand for space heating. In some cases, the age of the building has been used as a measure for individual design and innovation elements. This component of the research is especially interesting because it associates an increase demand for energy for space heating with particular building characteristics (Tommerup and Svendsen 2006).

Research done on the housing stock in the Netherlands by Tommerup and Svendsen (2006) highlights the correlation between building age, physical characteristics and energy demand. The study classified buildings into seven distinct time periods based upon changes in building design and form, and advancements in building technology (2006). One relevant component of the study showed how the energy loss from different parts of the building (floor, roof and exterior walls) increased with building age. By classifying buildings according to a time period associated with a building design or technological innovation, the researchers were able to explore the capacity of building retrofits to reduce energy demand within a cost-benefit framework (Tommerup and Svendsen 2006).

Research done in Italy examined a small sample of buildings to determine the relationship between energy demand and the thermo-physical factors that influence heat loss and inefficiency. The research found a positive relationship between building age and energy demand, further supporting the evidence of a correlation between building characteristics, age and energy demand (Caldera, Corgnati and Fillippi 2008).

Research on residential energy consumption in the United States has also examined the role of building age on energy consumption. A study by Nikhil Kaza used data from the Residential Energy Consumption Survey and found that living area, age of the structure, and energy price, had an impact on energy consumption for space heating (Kaza, 2010). Kaza's findings demonstrate that energy consumption for space heating increases approximately 5-14 kilowatt hours for 20-year increments at the upper tail of the consumption frequency distribution, however much of this increase in consumption as a result of building age can be offset by changes in consumption behavior. Kaza established five building classes, to examine the impact of age: Pre-1939, 1940-1959, 1960-1979, 1980-1999, and 2000+ (2010). Interestingly, Kaza found that the impact of price on curbing energy consumption was more significant than the impact of increased living area. The policy implication as a result of these findings is that regulating energy prices will have more significant impact on consumption than regulating building size (2010). The effect of household income on energy consumption was not significant in Kaza's research; with the inference being that high income households are more likely to use energy efficient appliances and live in buildings that have thermal properties which minimize heat loss (2010).

The role of housing typology on energy consumption is debatable; some claim that multi-family dwellings are inherently more efficient than single-family counterparts, while other evidence suggests multi-family units are more efficient to a point, but become less efficient as building size increases and more common area (hallways, utility areas) is added that is not used for living space (Staley, 2008). Research in Norway examined the impact of building codes on energy consumption, and found that single-family homes built after 1980 were significantly more energy efficient than single-family homes built previously, thus lessening the impact of multi-family housing units and urban form on household energy consumption for heating (Holden and Norland, 2005). Furthering the debate, research from Canada comparing energy consumption in low-density (single-family detached units) and high-density buildings (greater than 5 unit apartments) in Toronto found that energy consumption per unit of living area was less in single-family homes than in multi-family homes. However, the same analysis showed energy consumption per capita, was significantly greater in the low-density sample versus the high-density sample. This suggests that energy consumption is similar across housing typologies, with the difference largely being attributed to size, and the unit of analysis (Norman et al. 2006). The research related to housing typology and energy consumption suggests that the energy savings commonly associated with multi-family housing, is actually the result of living area, and not other physical characteristics of the buildings that make them more efficient than single-family dwellings.

2.3.3 Occupancy Characteristics and Energy Consumption

Research has also been done on the influence of occupancy characteristics on household energy consumption. These studies have specifically examined the role of tenure—renter versus owner occupied housing—and age of occupant on household energy consumption for space heating.

The relationship between tenure and energy consumption is not definitive but it appears to be most influenced by the policies in place to ensure energy efficiency in rental buildings and also by the nature of utility agreements in rental contracts. In Great Britain, research has shown that renter occupied dwelling units tend to use less energy compared to owner occupied dwelling units. The researchers suggest this is the result of renters occupying smaller dwelling units, and occupying more energy efficient buildings (Meir and Rehdanz, 2010). This study did not control for the effect of building age on energy consumption, so much of this variation could be the result the influence of dwelling size. Similar research done in Germany had conflicting results, as they found that energy consumption was greater in renter occupied housing units. By comparing monthly expenditures for heating, the researchers found that renters pay more on monthly heating expenses than owners. The researchers attributed the higher costs to inefficient buildings, which is the result of landlords not having any incentive to invest in building retrofits that prevent heat loss, when they are not paying the cost of utilities (Rehdanz, 2010). Research on the role of occupancy characteristics in the Netherlands supports the findings in Germany, suggesting that renter occupied units consume more energy for space heating (Santin et al., 2009).

Other occupancy characteristics, particularly age, have also been shown to have positive impact on energy demand for space heating. Research done by Liao and Chang (2002) sought to specifically examine the impact of age, on consumption of energy for space and water heating. Their research suggests that as occupants become older, the demand for space heating increases, while the demand for water heating decreases. This research broke age groups into different classes, and found that over the age of 60, residents consume more energy for space heating. These findings they believe, are caused by the aged spending more time at home (thus increasing demand) and due to the physiological effects of aging, that necessitate warmer indoor temperatures (2002). These findings are supported by research from the Netherlands that found similar impacts for the effect of age on energy consumption.

2.4 Summary

From the existing research, it is clear that there are several factors that influence household energy consumption for space heating. These factors can be broadly classified as building characteristics (living area, type, age) and occupancy characteristics (tenure, age) With the two most significant variables being living area and building age (Kaza, 2010). These variables are utilized in constructing a regression model to determine the influence on average household energy consumption for space heating across municipalities in Massachusetts.

CHAPTER 3

RESEARCH SCOPE AND METHODOLOGY

The methodology was informed by the literature review in Chapter 2, which discussed variation in energy consumption as it relates to the built environment, urban morphology, building and household characteristics. This research is concerned with measuring household energy consumption for space heating in municipalities across Massachusetts. To explore this relationship, a regression model is developed made up of dependent and independent variables. This section will discuss the assumptions, data sources, and variables included in the model.

3.1 Research Design and Scope

Chapter 2 provided a detailed discussion of the common methods used for measuring energy consumption, with “top-down” and “bottom-up” techniques discussed in detail. Because we are concerned with variation in energy consumption for space heating in Massachusetts, using highly aggregated energy consumption[1] data, as is done in “top-down” modeling techniques, is not particularly useful. At the same time, a “bottom-up” technique is restricted by its outside validity–how representative it is of the larger housing stock–and the time and resource constraints involved in developing complex building energy models. An alternative is a “hybrid” methodology that captures unique data about each spatial unit, which is then used in the development of a regression model, which attempts to explain the variables responsible for this variation. Multivariate regression is used to measure the relationship between a dependent variable (*y*) and multiple independent variables (x_1, x_2, x_3 etc).

$$y_i = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} \ldots$$

The benefit of using a multivariate regression is that it measures the effect of many independent variables on one dependent variable. This allows us to better understand the statistical significance and magnitude of each independent variable, while controlling for the interaction among the variables.

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[1] An example of this data is Residential Energy Consumption Survey Data. A highly aggregated national dataset comprised of household averages across the United States.

Based upon the available data sources, regression models were developed based upon two datasets. One dataset consists of 37 communities where assessors' data was obtained regarding building characteristics. These models are referred throughout the discussion and results as Level 1 models. The independent variables were constructed from assessors' data and the 2005-2009 American Community Survey. A second set of models was developed which consists of the 37 communities from the Level 1 models, along with 19 additional communities, for a total sample size of 56 municipalities. The Level 2 models include independent variables that were developed from the 5-year Estimates of 2005-2009 American Community Survey. Additional information about the data sources used in each model is included in this section.

3.2 Measurement of Dependent Variable

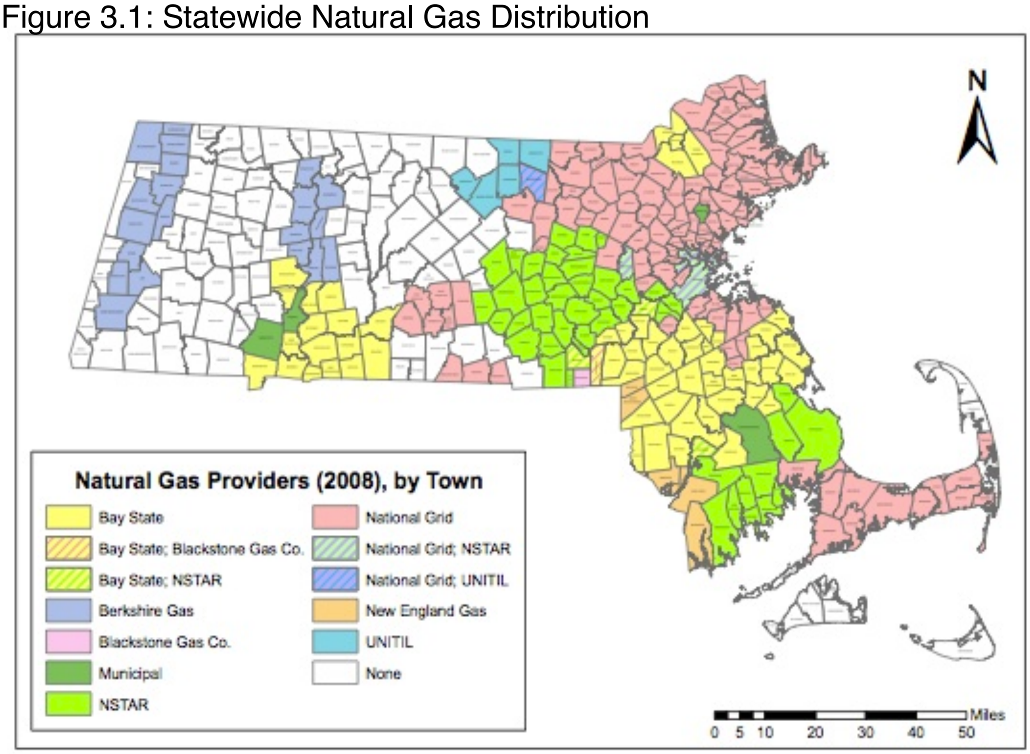
Accurately measuring residential energy consumption for space heating is one of the most challenging components of this research. In Massachusetts, the majority of household heating is derived from oil, natural gas, and electricity with the remaining households relying on other sources (Massachusetts Department of Environmental Protection, 2009) (Table 3.1). The composition of fuel types used in the housing stock of most municipalities is diverse and influenced largely by the available supply. For example, natural gas consumption is limited by service, at both the municipal and sub-municipal level. Several municipalities are not served by a centralized natural gas utility at all, while some municipalities may have some areas with service and others without service (Figure 3.1).

Table 3.1: Sample of Heating Fuel Type by Municipality

Municipality	Occupied Housing Units	Utility Gas	Electricity	Fuel Oil
Lawrence	23638	76%	11%	11%
Longmeadow	5453	72%	4%	22%
Haverhill	23750	71%	8%	19%
Sharon	5976	63%	7%	28%
Methuen	15851	63%	11%	24%
Marshfield	9147	62%	8%	27%
East Longmeadow	5602	61%	6%	31%
North Andover	10036	61%	12%	24%
Stoughton	9909	58%	9%	31%
Franklin	10924	57%	11%	29%
Springfield	56055	56%	15%	26%
Canton	8345	56%	14%	27%
Medfield	4096	56%	4%	39%
Foxborough	6251	56%	10%	31%
Andover	11597	55%	9%	33%
West Springfield	11839	54%	21%	23%
Agawam	11273	53%	18%	25%
Walpole	8496	53%	6%	38%
Scituate	6787	51%	4%	43%
Mansfield	8277	51%	17%	31%

*Data compiled from 2005-2009 American Community Survey, *Summary File*

Figure 3.1: Statewide Natural Gas Distribution

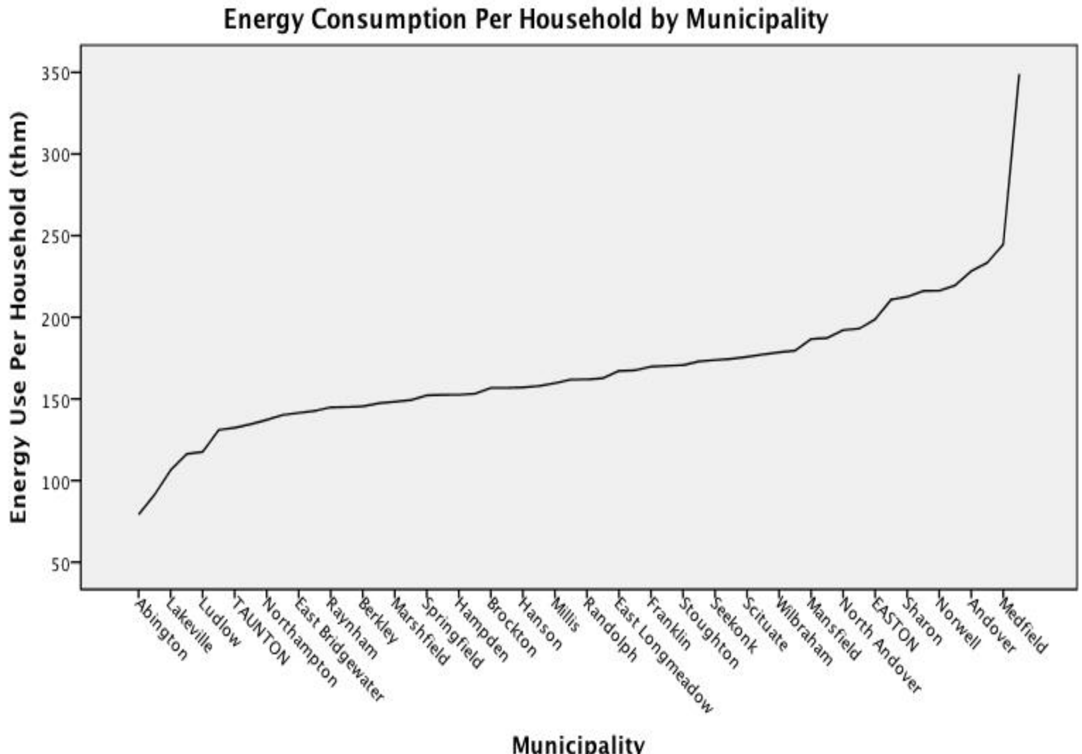


Source: Massachusetts Office of Geographic Information Systems, Massachusetts Executive Office of Energy and Environmental Affairs

The nature of fuel oil distribution across the state, which is largely comprised of small local suppliers, makes it nearly impossible to accurately measure consumption at the municipal scale. Compiling and aggregating these individual consumption records in a way that accurately reflects the overall consumption of the community is unfeasible.

For this research, a private natural gas utility operating in Massachusetts provided natural gas consumption data for all residential customers aggregated by municipality and zip code. In total, this provided a sample of 56 municipalities (see Appendix A for list of Municipalities). The data were provided by spatial unit in therms (thm) over a 12-month period from December 2009-November 2010. The dataset included the total number of customers per month, which allowed an average household consumption calculation to be determined for each municipality. The 12-month period of data allowed for the normalization of the data to account for non-space heating uses, such as water heating, dryers, stoves and other household appliances. The average household energy consumption for space heating in each municipality is shown in figure 3.2.

Figure 3.2: Average Household Energy Consumption by Municipality



Compiled from private utility data for natural gas consumption

While there appears to be an outlier in the average household energy consumption data for the municipalities within our sample, the characteristics of the homes within this community indicate this may be the result of significantly larger homes in this municipality. The median number of rooms in dwellings in this community is 9, versus the median for the sample of 6.3.

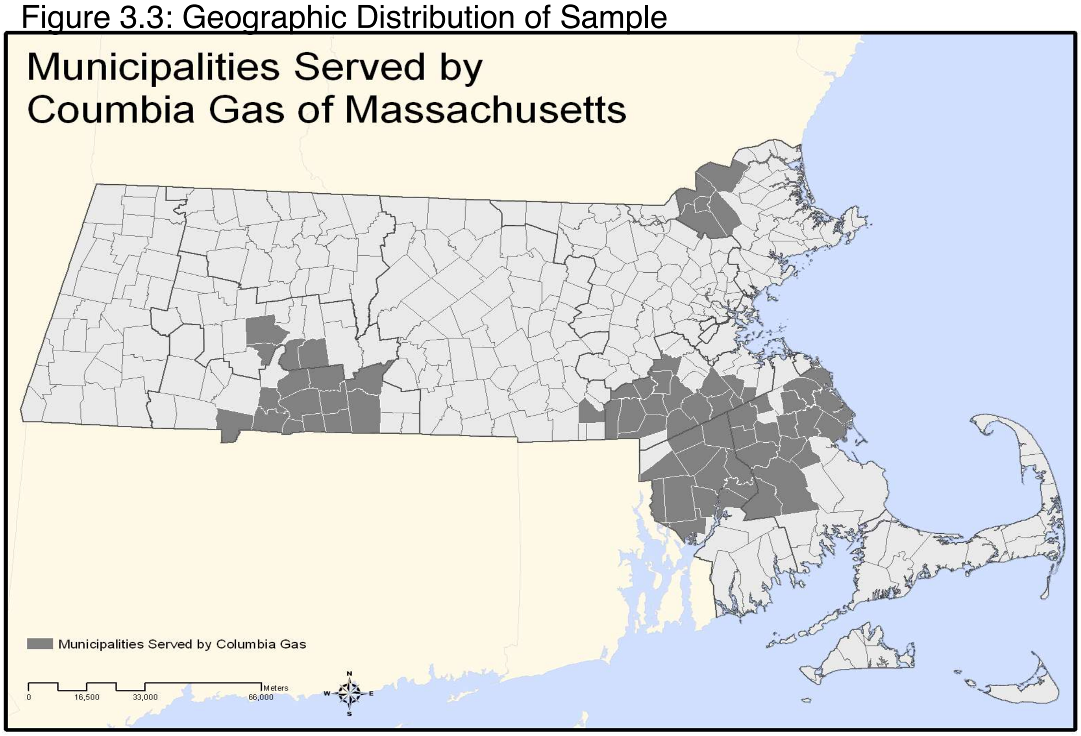
Table 3.2: Average Household Energy Consumption Descriptive Statistics

Statistic	Model 1	Model 2
n	37	56
Mean	176.4	167.9
Median	174	161.9
Std. Deviation	34.16	41.6
Range	165.1	269.9
25th Percentile	156.8	145.2
50th Percentile	174	161.9
75th Percentile	198.6	184.9
Inter-quartile Range	41.8	39.7

Compiled from private utility data for natural gas

The service area of the private utility that provided the energy consumption data for this research determines the geographic extent of our sample.

Figure 3.3: Geographic Distribution of Sample



3.3 Measurement of Independent Variables

The independent variables of interest are related to building characteristics and socioeconomic characteristics of the households. The selection of variables is based upon the review of the existing research on factors influencing energy consumption for space heating.

Housing Type (%) • Single-family • 2-4 Family Apartments • 5-19 Unit Apartments • More than 20 Unit Apartments	• % of Population Over 65+ • %Renter Occupied • % Owner Occupied • Median Household Income • Mean Living Area • Median Number of Bedrooms	**Building Age (%)** • % Pre 1939 • % 1940-1959 • % 1960-1979 • %1980-1999 • %2000+

3.3.1 Data Sources

The data sources for the independent variables were obtained from the assessing departments of the sample municipalities and the 2005-2009 *American Community Survey* (ACS), 5-year estimates. Both these sources provide detailed descriptions of the physical characteristics of the housing stock, and the ACS provides data about household occupancy characteristics. The advantage of obtaining data from the individual assessors departments is that it is a more accurate description of the physical characteristics of the housing stock than the census data. From these records, we are able to obtain detailed information about the size of buildings and the year each was built. Because the records include information about the type of fuel used for each housing unit, living area and year built data is specific for homes that use natural gas for space heating. Fortunately, this detailed level of data was only available for 37 of the 56 municipalities. More information about how this data was included in the model will be discussed in detail later in this chapter.

Fortunately, the release of ACS provides the necessary data for the physical and household occupancy characteristics for all of the municipalities in our sample. While, this data are not as accurate as the assessors' data for the physical characteristics of the housing stock, as will be discussed in later sections, it serves as good proxies for the variables of interest. The next section will provide discussion of the hypothesized relationships and descriptive statistics about each independent variable.

3.3.2 Mean Living Area

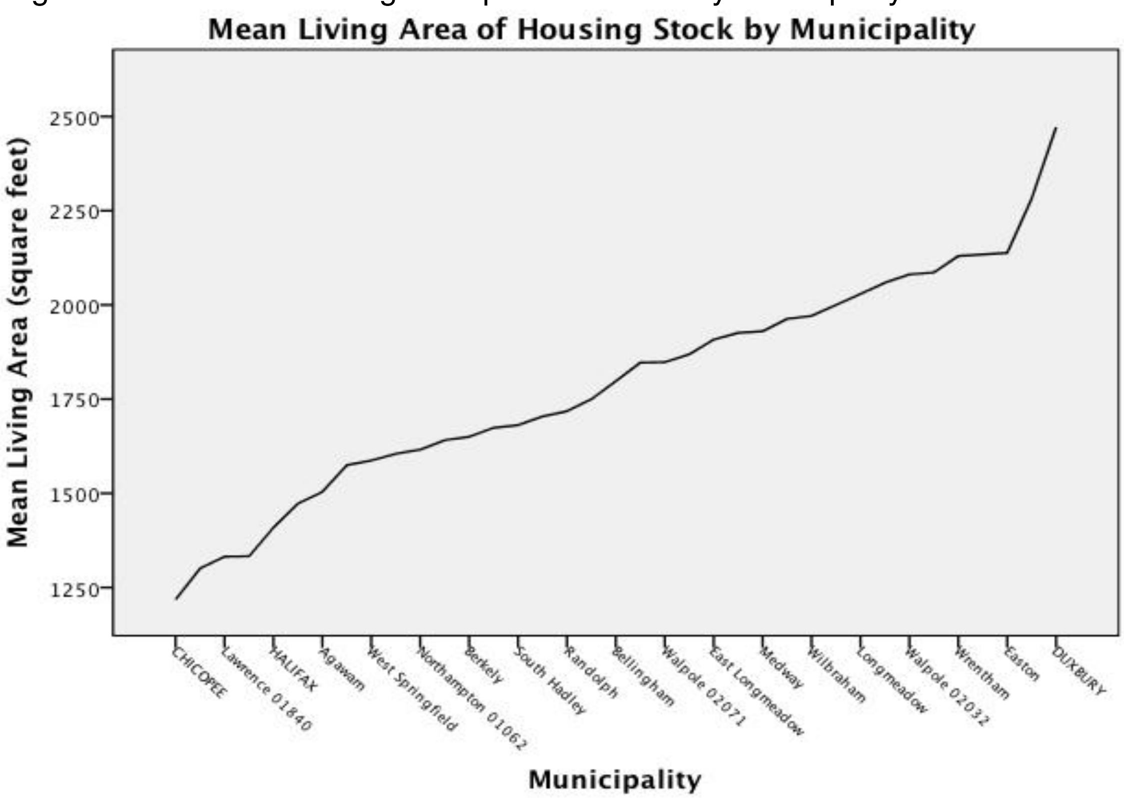
The mean net living area variable is used in the model to control for the effect of building size on energy consumption. Mean living area data is only available from the 37 municipalities where assessors' data was collected. This data is utilized in the Level 1 models to understand the effect of building age on energy consumption. The data is also useful in assessing the accuracy of the ACS data that are used for a living area control in the Level 2 model. Based upon a Pearson Correlation Coefficient test we see that the median number of rooms data from the ACS and mean net living area by municipality from the assessors' data are highly correlated. Table 3.4 provides a descriptive summary of the data and Figure 3.6 provides a visual summary.

Table 3.3: Net Living Area Descriptive Statistics

Statistic	Model 1
n	37
Mean	1790.32
Median	1798
Std. Deviation	292.6
Range	1254
25th Percentile	1596
75th Percentile	2014.5
Inter-quartile Range	418.5

Data compiled from municipal assessor's data

Figure 3.4: Mean Net Living Area per household by municipality



Data compiled from municipal assessor's data

3.3.3 Median Number of Rooms

Median number of rooms is used as a measurement for net living area in the *Level 2* models where detailed assessors information was not available. Fortunately, we can use our mean living area data from the assessors records to understand how well median number of rooms serves as a measure of living area. Calculating the correlation coefficient of the two variables shows that median number of rooms serves as a good proxy for living area.

Table 3.4: Pearson Correlation Coefficient Median Rooms and Net Living Area

	Median Rooms	**Net Living Area**
Median Rooms Pearson Correlation	1	.797**
Net Living Area Mean	.797**	1

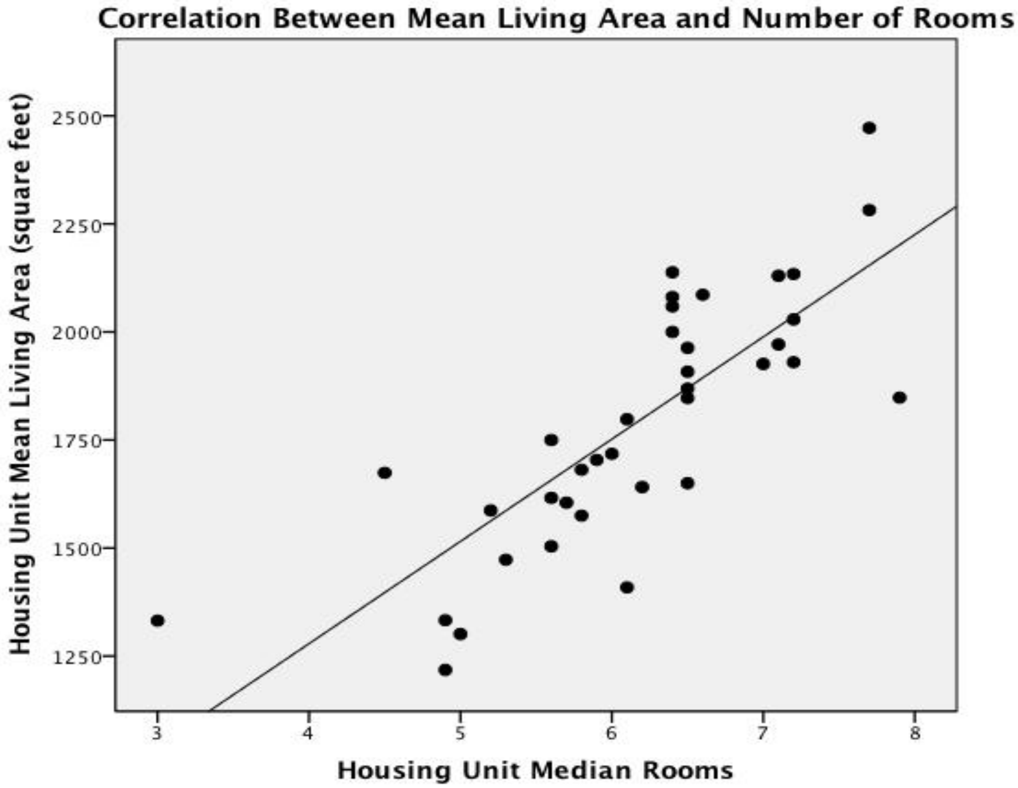
**Results are statistically significant at the .01 level

Table 3.5: Median Number of Rooms Descriptive Statistics

Statistic	**Model 1**	**Model 2**
n	37	56
Mean	6.2	6.3
Median	6.4	6.3
Std. Deviation	.83	.81
Range	3.1	4.2
25^{th} Percentile	5.6	5.8
75^{th} Percentile	6.4	6.7
Interquartile Range	.8	.85

*Data compiled from 2005-2009 American Community Survey, *Summary File 3*

Figure 3.6: Mean Living Area and Median Number of Rooms Correlation



*Data compiled from 2005-2009 American Community Survey, *Summary File 3* and municipal assessor's data

3.3.4 Average Household Size

Average household size is used as a control in our model to account for the effect of increased occupancy and energy consumptions. It is not expected that this will have a significant impact based upon the existing research, but it is included to account for any change. If this research was examining residential energy consumption as a whole, it is expected that this would make more of a difference due to increased usage of appliances and other electronics, but I don't think occupancy levels will significantly increase energy demands for space heating.

3.3.5 Building Age

Building age is believed to be one of the primary factors that contribute to energy consumption for space heating in the model. Previous research in both Europe, and the United States has shown that building age is highly correlated with increased energy consumption. The building age data comes from three separate data sources and is distinct to each scale of the model. The *Level 1* model utilizes building age data from the assessor's records of the 37 municipalities. This data is believed to be the most accurate and representative of the sample because the data was organized to only include homes that use natural gas for space heating. This data is only included in the *Level 1* model however. The *Level 1I* model, which includes 56 municipalities, utilized median year built data from the 2005-2009 ACS 5 year-estimates. The structure of the data allows us to classify the building stock based upon decade built, however we are unable to isolate our sample to homes that use natural gas.

The building age is broken down into five classifications. The classification is based upon research done at the Lawrence Berkeley National Laboratory on the energy load demands of the US building stock. Although the research was done in the early 1990's the classification remains relevant, and it can be inferred that the classification is largely done based upon changes in the construction styles. For the *Level 1* and *Level 1I* models, the buildings were broken down into five classes.

- Pre 1939
- 1940-1959
- 1960-1979
- 1980-1999
- 2000+

In addition to these classes an additional variables was created, homes built after 1980+ to control for the effect of newer single-family homes on energy consumption.[2]

The building age classifications are correlated with the post World War II housing boom in the 1950s, and the adoption of standardized building codes in the late 1970s. The first building code in Massachusetts was passed in 1975 and required insulation of all interior wall cavities. Based upon the existing literature review and other research, it is believed that as buildings age, they will consume more energy, due to air leakage and other inefficiencies (Ritschard et al. 1992).

Table 3.7: Building Age Variable, Level 1 Model, Descriptive Statistics

Statistic	**Pre-1939**	**1940-1959**	**1960-1979**	**1980-1999**	**1980+**	**2000+**
n	37	37	37	37	37	37
Mean	.24	.20	.27	.24	.30	.06
Median	.19	.19	.26	.22	.27	.07
Std. Deviation	.12	.07	.06	.10	.12	.03
Range	.36	.30	.22	.40	.48	.11
25th Percentile	.15	.15	.22	.17	.18	.05
75th Percentile	.30	.26	.31	.31	.38	.09
Interquartile Range	.15	.11	.09	.14	.20	.04

Data compiled from 2005-2009 American Community Survey, *Summary File 3*

[2] This will be discussed in greater detail in the results section.

Table 3.8: Building Age Variable, Level 2 Model, Descriptive Statistics

Statistic	Pre-1939	1940-1959	1960-1979	1980-1999	1980+	2000+
n	56	56	56	56	56	56
Mean	.20	.20	.28	.25	.31	.07
Median	.18	.19	.28	.24	.29	.07
Std. Deviation	.10	.07	.06	.09	.12	.03
Range	.40	.30	.26	.40	.50	.19
25th Percentile	.14	.15	.24	.18	.23	.05
75th Percentile	.28	.25	.34	.31	.29	.09
Interquartile Range	.14	.10	.10	.13	.15	.04

Data compiled from 2005-2009 American Community Survey, *Summary File 3*

Based upon the frequency distribution in both models we can see there is more variation in the percentage of homes built prior to 1939 and those homes built after 1980 with standard deviations of .10 and .12 and interquartile ranges of .14 and .15 respectively.

3.3.6 Housing Tenure

Tenure**,** and more specifically, renter occupied housing is believed to be a significant factor influencing average household energy consumption for two reasons:

1. In renter occupied structures the landlord has little incentive to improve the energy efficiency of the building when the renter pays utility costs directly, and renters have little incentive to make efficiency improvements in buildings that they do not own.

2. When renters do not pay utilities, and therefore have little incentive to conserve energy. Table 3.9 shows the descriptive statistics for renters, while Figure 3.7 graphs the proportion over our *Level 1* study area in order to show the variation.

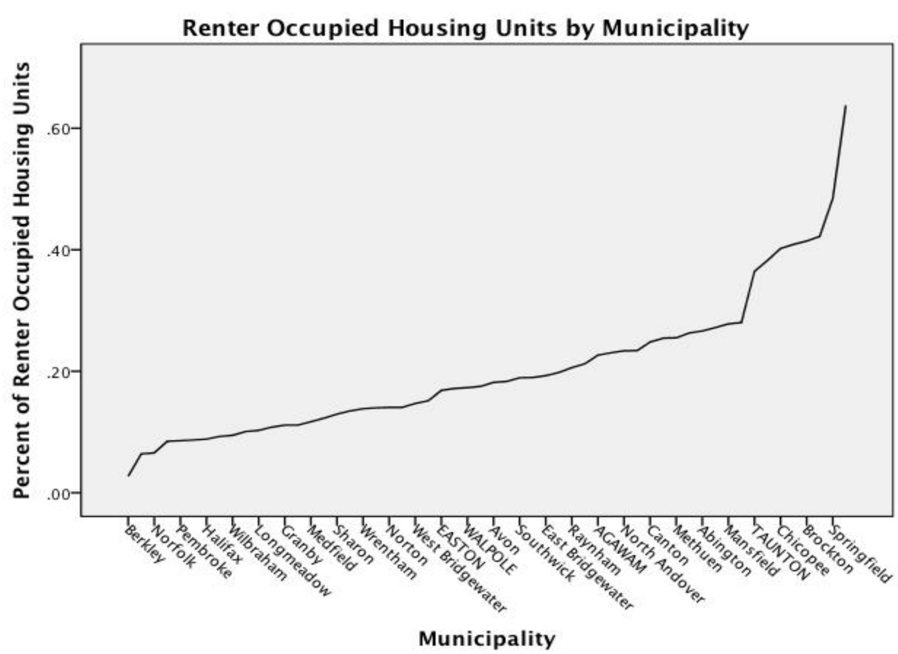
This issue is commonly referred to as the split incentive.

Table 3.9: Percentage of Renter Occupied Housing, Descriptive Statistics

Statistic	Model 1	Model 2
n	37	56
Mean	.23	.20
Median	.17	.18
Std. Deviation	.15	.12
Range	.55	.61
25th Percentile	.11	.11
75th Percentile	.33	.26
Interquartile Range	.22	.15

Data compiled from 2005-2009 American Community Survey, *Summary File 3*

Figure 3.7: Percentage of Renter Occupied Housing, Level 2 Model



3.3.7 Age of Household Occupant

Previous research suggests a positive relationship exists between age of householder and energy consumption. Research by Liao and Chang (2002) suggests this variation is based upon the lifestyle of the aged, and more specifically, the population over 65 years old. Because the older proportion of the population tends to be retired and spend more time at home, heating demand is higher as higher average indoor temperatures are maintained for longer periods throughout the day. Based upon this research, the percentage of households with an occupant over the age of 65+ was tabulated from the ACS data to examine the impact older populations' lifestyle has on energy consumption for space heating.

3.3.8 Housing Typology

There is significant evidence to suggest that housing type has an impact on energy consumption when controlling for living area. As discussed in the literature review, there is some debate about the degree to which multi-family dwellings impact energy consumption. We break buildings down into 4 classes to examine this effect.

- Single-family Attached and Detached
- 2-4 Unit Dwellings
- 5-19 Units
- 20+ units.

Table 3.10: Housing Unit Type by Percentage, Descriptive Statistics

Statistic	Single-Family	2-4 Family	5-20 Units	20+ Units	All Multifamily Units*
n	56	56	56	56	56
Mean	.77	.11	.07	.04	.22
Median	.78	.08	.07	.04	.19
Std. Deviation	.15	.09	.05	.03	.15
Range	.69	.47	.17	.14	.69
25th Percentile	.69	.04	.02	.01	.09
75th Percentile	.90	.15	.11	.07	.31
Interquartile Range	.21	.11	.09	.06	.22

*All multi-family units is calculated by adding all of the multi-family units together
Data compiled from 2005-2009 American Community Survey, *Summary*

The Pearson Correlation Coefficient test shows the strong correlation between all multi-family units and renter occupied units. This is not surprising but is important to consider in the development of the models because it will be nearly impossible to differentiate the influence of renters and building typology on energy consumption.

Table 3.11: Pearson Correlation Coefficient Percentage of Renters and Percent Multi-Family Housing Units

	Multi-family Units	Percent Renters
Multi-Family Units Pearson Correlation	1	.97**
	.97**	1

Data compiled from 2005-2009 American Community Survey, *Summary File 3*

CHAPTER 4

RESULTS

4.1 Level 1 Model Analysis

Data Sources: Assessors' Data, 2005-2009 American Community Survey

The *Level 1* models were developed in order to determine the impact of dwelling size and building age on average household energy consumption for space heating. From this data I was also able to determine the degree to which median number of rooms is an accurate control for dwelling size by comparing the regression results using median number of rooms and mean net living area as control variables. Due to the small sample size statistically robust models with multiple independent variables could not be developed from this dataset, however they are helpful in the understanding of the *Level 2* model results.

The first models explore the relationship between energy consumption and building size using the two different controls for size: mean net living area and median number of rooms. The results indicate that median number of rooms data from the census, while not as robust as net living area from the assessors records, is an adequate proxy for building size. This is beneficial to the development of the Level 2 variables.

Table 4.1: Level 1 Regression, Net Living Area and Median Rooms

n	**Dependent Variable**	**Independent Variables**	**R^2**	**Adjusted R^2**	**Std. Error**	**Beta**	**t**	**P-Value**
37	Thm/HH	Mean NLA	.363	.345	27.7	.602	4.6	.000
37	Thm/HH	Median # of Rooms	.328	.309	28.39	.573	4.14	.001

Based upon these results, mean living area is a stronger control for size than median number of rooms, with larger adjusted R^2 values and higher beta coefficients. Median number of rooms will still serve as an effective control for size in the *Level 2* models, which is important to the interpretation of the results. The next step in the *Level 1* analysis was to examine the role of building age on energy consumption. This dataset, while small, utilized building age data from assessors records so it is believed that we will see statistically significant results in our model due to the accuracy of the data. The building age variable is measured as a proportion of the overall housing stock. Due to the small sample size, the different building classes were treated as unique variables and added individually.

Only two building eras, those built prior to 1939 and those built after 2000 returned statistically significant results. Both of these variables were examined using the two controls for housing unit size.

Table 4.2: Level 1 Regression, Building Age

n	Dependent Variable	Independent Variables	R^2	Adjusted R^2	Std. Error	Beta	t	P-Value
37	Thm/HH	Constant	.45	.41	26.2		.322	.75
		Mean NLA				.731	5.22	.000
		%Pre-1939				.315	2.25	.031
37	Thm/HH	*Constant*	.43	.40	26.5		-.511	.613
		Median #Rooms				.82	5.10	.000
		%Pre-1939				.51	3.14	.003
37	Thm/HH	*Constant*	.56	.54	23.22			.16
		Mean NLA				.81	6.47	.000
		%2000+				-.50	-3.96	.000
37	**Thm/HH**	***Constant***	.40	.36	27.24			.05
		Median # Rooms				.65	4.60	.000
		%2000+				-.38	-2.72	.010

Homes built after 2000+ had the highest r^2 value at .545 and a beta coefficient value of -.51, meaning as the percentage of homes built after 2000 increased, average household energy consumption decreased. The results of the building age model are affected by the nature of the sample. In examining the frequency of our building age distribution, it is evident that there is more variability within our building age sample in older building (pre 1939) and newer buildings (post 2000), which influences our results.

From these results we see communities with larger proportion of older housing may have larger average household energy consumption for space heating. The lack of variation among other buildings is likely due to homogeneity of the data for housing in the middle of the twentieth-century, but also likely the result of wide ranges of building types and energy demands for these buildings. The findings suggest older building may consumer more energy, while newer buildings consume less. However, based upon the small sample if it is difficult to determine if this is only the effect of building age and not other factors.

4.2 Level 2 Model Analysis

Data Sources: 2005-2009 American Community Survey

The *Level 2* model includes data from 56 municipalities and draws entirely from the 2005-2009 ACS survey for the independent variables. The hope is that by increasing the sample size the other independent variables will become statistically significant and the factors influencing household energy consumption will be better understood.

With the larger sample size I begin by running a model to determine the impact of building age on average household energy consumption. I exclude the newest class of buildings (%2000+) to examine the impact that the percentage of older buildings may have on energy consumption.

Table 4.3: Level 2 Regression, Building Age by Class and Tenure

	Dependent Variable	**Independent Variables**	**R^2**	**Adjusted R^2**	**Std. Error**	**Beta**	**t**	**P-Value**
56	Thm/HH	*Constant*	.25	.19	37.83		-2.16	.04
		% Pre-1939				1.170	2.63	.011
		%1940-1959				.814	2.40	.02
		%1960-1979				1.06	3.53	.001
		%1980-1999				1.54	2.93	.005
56	Thm/HH	*Constant*	.71	.68	23.65			
		Median # of Rooms				.86	8.8	.000
		% Pre-1939				.83	2.92	.005
		%1940-1959				.40	1.81	.08
		%1960-1979				.46	2.27	.028
		%1980-1999				.67	1.93	.059
56	Thm/HH	Constant	.80	.80	19.54			.
		Median # of Rooms				1.20	11.27	.000
		% Pre-1939				.433	1.75	.09
		%1940-1959				.44	2.42	.02
		%1960-1979				.38	2.28	.03
		%1980-1999				.622	2.17	.04
		%Renter Occupied				.66	4.93	.000

Based upon the results of this model, we can see all the building class variables have a positive relationship with average household energy consumption. This suggests the variation among the building class variables is limited, or the variation in energy consumption related to age is somewhat marginal. Surprisingly, percentage of buildings built between 1980-1999 has the largest beta coefficient in the model when we control for the effect of tenure (renter occupancy). Also interesting is that when we control for the effect of tenure, the beta coefficient for buildings built before 1939 goes from .83 (without renter occupancy control) to .433. This suggests that renter occupancy in older buildings has an impact on average household energy consumption. Renter occupancy does not have a similar affect on buildings built between 1980-1999. This is not surprising, given that renters are more likely to inhabit older buildings.

To better understand the relationship of housing typology, the renter variables was removed from the model and replaced with the three classes of multi-family housing units. While the results, detailed in Table 4.4, are not statistically significant, they do suggest that multi-family homes of 2-4 units have a statistically significant influence on energy consumption, and a beta coefficient of .37. The beta coefficient for 5-20 unit buildings, and 20+ unit buildings are .17 and .16 respectively, and neither were statistically significant at the 95% confidence interval.

Table 4.4: Level 2 Regression, Building Age by Class and Housing Type

n	Dependent Variable	Independent Variables	R^2	Adjusted R^2	Std. Error	Beta	t	P-Value
56	Thm/HH	Constant	.81	.77	19.85		-4.21	.000.
		Median # of Rooms				1.20	11.27	.000
		% Pre-1939				.36	1.33	.19
		%1940-1959				.37	1.90	.06
		%1960-1979				.30	2.28	.09
		%1980-1999				.45	2.17	.04
		%2-4 Units				.37	1.33	.02
		%5-20 Units				.17	1.88	.066
		%20+ Units				.16	1.62	.11

The positive relationship between energy consumption and multi-family housing is somewhat surprising, because it is generally accepted that multi-family housing is more efficient than single-family housing. However, from a Pearson Correlation Coefficient test we can see the strong correlation between multi-family housing and older dwellings.

Table 4.5: Pearson Correlation Coefficient, Multi-family Units and Percent Housing Built Before 1939

	All Multi-family Units	Pre 1939 Units
All Multi-family Units Pearson Correlation	1	.718**
Pre 1939 Units	.718**	1

These findings suggest the relationship between building typology and energy consumption could be influenced by tenure. This is consistent with the research that suggests that multi-family dwelling units have not been retrofitted for energy efficiency improvements at the rate of their single-family counterparts because of the split incentive problem (Bamberger, 2010). Because multi-family buildings are highly correlated with renter occupied dwellings we will use renter occupied buildings as a measurement for multi-family units in the remaining models.

Table 4.6: Pearson Correlation Coefficient, Multi-family Units and Percent Renter Occupied Housing

	Multi-family Units	Percent Renters
Multi-Family Units Pearson Correlation	1	.97**
Percent Renters	.97**	1

In order to better understand the role of tenure and housing typology I developed a model that explores the relationship between energy consumption and single-family homes when controlling for the effect of age.

Table 4.7: Level 2 Regression, Building Age by Class and Tenure

n	Dependent Variable	Independent Variables	R^2	Adjusted R^2	Std. Error	Beta	t	P-Value
56	Thm/HH	Constant	.81	.79	19.05		-3.63	.001
		Median # of Rooms				1.26	11.51	.000
		% Pre-1939				.49	2.09	.04
		%1940-1959				.49	1.90	.008
		%1960-1979				.30	2.28	.02
		%1980-1999				.61	2.17	.03
		% SF Homes				-.67	1.33	.00

The results of the model are statistically significant and suggest and inverse relationship between percentage of single-family homes and average household energy consumption. This is not surprising, as single-family homes are more likely to be owner occupied and more likely to utilize energy efficiency retrofits.

When running the model for the other occupancy characteristics, including household size, and percent of the population over 65+, the results are not statistically significant. Based upon the aggregated level of this data, these results are not particularly surprising.

CHAPTER 5

DISCUSSION

The results of the regression model are consistent with the initial hypothesis about the relationship between the independent variables and average household energy consumption for space heating. Although, tenure had a more significant impact than originally expected and the impact of building age was less significant than originally hypothesized. The key findings of the research include:

1. Variation exists in average household energy consumption among municipalities in Massachusetts.
2. Median Number of Rooms data available from the American Community Survey is an acceptable control variable for dwelling size.
3. Net living area and median number of rooms have a statistically significant positive relationship with average household energy consumption.
4. Tenure, and more specifically, proportion of renters, has a statistically significant positive relationship with average household energy consumption. Although, due to the small sample size it is difficult to determine if this is the result of renters living on older buildings or some other cause, such as the split incentive problem.
5. Multi-family buildings, and more specifically percentage of 2-4 unit buildings have a statistically significant impact on average household

energy consumption and the most significant beta coefficient among multi-family dwellings.

The key findings will be discussed in greater detail with respect to how they relate with the existing research and our understanding of the factors influencing household energy consumption.

1. Variation exists among municipalities in average household energy consumption for space heating.

Although this finding is not particularly surprising, it is critical to the research. A primary assumption in engaging the research question was that among municipalities there would be variation in average household energy consumption for space heating. In obtaining data for energy consumption for space heating aggregated at the municipal level, this variation was found to exist. This is particularly important from a policy perspective because this variation could be targeted in prioritizing energy efficiency investments.

2. Median Number of Rooms data available from the census is an acceptable measurement for average net living area

For the purposes of this research, as well as future research endeavors, it is worth recognizing that median number of rooms data, available from the U.S. Census and ACS, is a good measurement for mean net living area. Net living area was an important control variable used within the models developed for this research and the correlation coefficient among net living area—as calculated from assessors' data—and median number of rooms from the ACS is .797. This suggests the variables are highly correlated.

3. Net living area and median number of rooms have a statistically significant positive relationship with variation in average household energy consumption for space heating.

These results are not surprising, as one would expect as average net living area increases average household energy consumption would also increase. The results are interesting from a policy and equity standpoint because the implication is that larger homes should potentially be targeted for energy efficiency improvement because they could have more potential energy savings per unit of investment.

4. **Tenure, and more specifically, proportion of renters, has a statistically significant positive relationship with average household energy consumption. Although, due to the small sample size it is difficult to determine if this is the result of renters living on older buildings or some other cause, such as the split incentive problem.**

The *Level 2* models provide more robust and statistically significant results in comparison to the *Level 1* models, which allows us to examine the impact of other variables, beyond building age, on energy consumption. From these models we can begin understand the role of housing type on energy consumption and how this relates to owner versus renter occupied dwellings.

The results of the regression model indicate a statistically significant positive relationship between the percentage of renter occupied dwellings and average household energy consumption. This seems to reflect the 'split incentive' problem with multi-family dwellings that has been addressed in the literature (Bamberger, 2010). Interestingly, it appears as though there is a relationship between older buildings and renter occupied dwellings, as the beta coefficient for the % pre 1939 housing unit variable decreased significantly when the % renter variable was added to the regression.

5. Multi-family buildings, and more specifically % 2-4 unit buildings have a statistically significant impact on average household energy consumption and the most significant beta coefficient among multi-family dwellings.

The results of this model were statistically significant and show a positive relationship between percentage of multi-family housing units and average household energy consumption. This is likely the result of the 'split incentive' problem. Interestingly, 2-4 family units had the most significant beta coefficient among the multi-family variables.

These results are interesting because it is commonly accepted that multi-family buildings are more energy efficient than single-family homes, while these results indicate this may not necessarily be the case (Ewing, 2008).

CHAPTER 6

CONCLUSION

6.1 Policy Implications

The goal of this research was to determine if average household energy consumption for space heating varied across municipalities and to then understand the factors influencing this variation. This question is important because energy efficiency in buildings and sustainability in general, are increasingly being addressed through a variety of government polices and programs. The weakness of many of these interventions however is a lack of empirical evidence to measure energy efficiency programs and in turn justify the government expenditures. This makes it difficult to not only estimate program expenditures, but also to strategically target investments to maximize energy savings and return on investment.

Although, the findings of this research cannot answer the question of return on investment for energy efficiency improvements definitively, they do help us understand some of the factors that influence energy consumption for space heating in residential buildings, and in doing so they help frame the discussion of how to prioritize investments funded through government and utility sponsored energy efficiency programs. The findings of this research and the existing research on the subject indicate government policies and programs could be restructured to better target efficiency resources in a more strategic approach (Bamberger, 2010). This approach would involve targeting resources at energy intensive communities with large renter populations. The major policy recommendations based upon this research are:

1. Restructure landlord-tenant utility contracts to increase demand among landlords and tenants for energy efficiency building retrofits.
2. Develop an Energy Efficiency Block Grant program (EEBG) administered through local governments that awards funding for residential energy efficiency retrofits to municipalities based upon entitlement and competitive criteria.

These policies are intended to be cumulative in that the first policy must be implemented to catalyze the demand for energy efficiency retrofits, before the second policy can be deployed which targets specific municipalities for energy efficiency retrofits through a competitive, need-based, block grant program. The following section will each of these policy recommendations in more detail.

Restructure landlord-tenant utility agreements so both parties have incentives for energy efficiency through green leases and the elimination of master metered buildings.

As this research shows, renter-occupied dwelling units have a positive impact on average energy consumption for space heating. This finding is supported by other research that indicates multiple-family buildings are rarely targeted for energy efficiency retrofits, despite the fact that multi-family buildings make up nearly 18 percent of the U.S. housing stock (Bamberger, 2010). Because multi-family buildings generally tend to be on average older than single-family dwellings, it is not surprising that a positive relationship with average household energy consumption was observed as the percent of multifamily dwellings increased. Because multi-family dwellings are typically smaller than single-family dwellings, this finding is somewhat surprising, but likely the result of two causes which have direct policy implications:

1. The 'split incentive' problem in which the landlord has little incentive to make energy efficiency improvements in a building where tenants pay utility costs, and the tenant has little incentive to make capital investments in a building that they hold no ownership in.
2. In approximately one-quarter of all rental agreements in the United States tenants do not pay utilities as a separate payment from monthly rent. Research has shown this group of consumers tends to consume more energy for space heating than renters who pay utility costs directly (Levinson, 2005).

The split incentive is problematic because it creates a barrier to energy efficiency investments (Bamberger, 2010). With respect to space heating, there is little a tenant can feasibly do to the building shell improve energy efficiency.

The responsibility to retrofit then falls to the landlord to make efficiency improvements that do not demonstrably make the building more valuable, in terms of resale, or as a rental property.

One approach that is beginning to be utilized to solve the split incentive stalemate is the 'green lease,' whereby tenants agree to a relatively nominal increase in rent and landlords agree to upgrade the building with efficiency improvements, which will reduce the tenant's monthly utility bills. This approach has been most successful in restructuring the incentive structure of commercial real estate and is only beginning to be utilized in the residential sector (Enterprise Communities, 2011). There are certainly coordination problems with the 'green lease'—getting all tenants to agree to a rent increase and maximizing the economic benefit to the property owner— but these could potentially be mitigated by incorporating a 'green lease' as a requirement for all properties that receive state, federal, or utility sponsored funding for residential energy retrofits. In an effort to mitigate the landlords risk, the marginal rent increase could potentially be used as a tax abatement the first few years after the program initiation, so the landlord could charge the same rent—to avoid losing tenants—while increasing the efficiency of the building.

Another policy is more directly aimed at promoting energy conservation by changing tenant behavior. Approximately 25% of all renters in the U.S. do not pay utilities as a separate cost of rent, and while this is partially related to the landlords' inability to accurately measure individual energy consumption in master-metered buildings, this is not always the case.[3] Research has shown renters who do not pay utilities as a separate cost from rent tend to keep units warmer and as a result consume more energy for space heating compared to tenants who pay utility costs directly (Levinson, 2005). Policies should be implemented that encourage landlords to separate the cost of utilities from rents. This is particularly attractive because it involves minimal capital investment and only the willingness of the landlord to engage in changing the structure of rental contracts. Furthermore, the research indicates that these rental agreements are not financially beneficial for landlords; tenants typically consume more energy than the landlord recoups in the increased rents for utility included apartments (2005).

Develop an Energy Efficiency Block Grant program (EEBG) administered through local governments that awards funding for residential energy efficiency retrofits to municipalities based upon entitlement and competitive criteria.

While the first policy recommendation sought to improve the efficiency of multi-family dwellings through changing the incentive structure for conservation, the second recommendation is more directly related to strategically allocating investments in energy efficiency resources in a cost effective, strategic framework.

[3] Master-metered buildings are those with one utility meter that measures energy consumption for an entire building and not individual units.

The research was influenced by the hypothesis that average household energy consumption would vary across municipalities and the variables influencing this variation—dwelling size, building age and tenure— could potentially be targeted at the municipal level in order to maximize economies of scale in implementing energy efficiency retrofits by targeting efficiency improvements at municipalities where average household energy consumption is considerably larger than the mean of the sample population.

This section will discuss the existing federal and state programs which provide funding and financing for residential energy efficiency retrofits and consider how they could be restructured in a way that would help catalyze energy efficiency improvements targeted at older, multifamily dwelling units. This is done by integrating a competitive grant process into the allocation of energy efficiency resources and ensuring the resources are administered to local governments in an effort to ensure the funding goes to improving efficiency in the most energy inefficient buildings.

Historically, the federal government role in residential energy efficiency retrofits has been through the Department of Energy's (DOE), Weatherization Assistance Program (WAP). WAP provides funding for a variety of weatherization improvements aimed at reducing low-income residents energy burden. In recent years this has change as more government programs targeting residential energy efficiency retrofits have been created and WAP's funding has been expanded. The Department of Housing and Urban Development (HUD) has created additional programs, such as the Green Retrofit Program, which aims to improve energy efficiency throughout their portfolio of publicly owned and publicly subsidized buildings. More recently, HUD has partnered with Fannie Mae to create Green Finance Plus, a program targeted specifically at increasing the financing opportunities available to owners of older multi-family buildings to perform energy efficiency retrofits (Bamberger, 2010).

In Massachusetts, the MASSave program is a utility administered efficiency program that targets improvements in building energy efficiency in a similar approach. MASSave offers funding assistance based on need and participation is entirely voluntary and dependent upon the property-owners initiative in engaging the process. The program offers energy audits, as well as weatherization assistance to homeowners in an effort to save money and reduce greenhouse gas emissions.

While the federal and utility-administered programs have varying requirements, they are similar in their general administration: funding is allocated to local non-government organizations, which are responsible for coordinating energy efficiency upgrades with local property owners. Aside from providing capital for energy efficiency improvements, most of these programs specifically target assistance at low-income households for efficiency improvements in order to reduce their energy bills. One major hurdle for these programs however is that they are dependent upon the property owners willingness to participate and this research as well as other studies suggest, that owners of multifamily dwellings have been slow to adopt these energy efficiency improvements.

One potential way of catalyzing energy efficiency improvements in multi-family dwellings and other dwellings that are large consumers of energy is to integrate a competitive block grant program element into funding for energy efficiency retrofits. With the goal being to put the onus on local governments to become the administrator of energy efficiency programs, or to at lease have a vested interest in seeing that their community is doing everything in their power to ensure that energy efficiency retrofits are targeted at dwellings that are high-energy households. In an era of constrained municipal budgets, these "Energy Efficiency Block Grants (EEBG)" would provide funding for municipalities to administer capital to local property owners for energy efficiency retrofits. The benefit of a block grant program is that it would enable communities to build local capacity for implementing an energy efficiency retrofit plan, while also holding them accountable to target resources in a manner that ensures they go towards dwellings with high-energy demands and significant potential for efficiency improvements.

HUD has many programs in place that could serve as a framework for creating the structure for an EEBG program. HUD uses an entitlement process and a competitive process in the allocation of many of its grant programs. The Community Development Block Grant program is awarded on an entitlement basis, which is determined by a broad set of socioeconomic indicators in a community. Other programs are awarded on a competitive basis, which would be assessed by the community capacity to spend resources in the most constructive way.

Creating an EEBG program in Massachusetts and other states could be an excellent way to spur energy efficiency investments while targeting communities with the most need for energy efficiency improvements. Based upon this research and the existing body of research on factors influencing energy consumption for space heating, a set of indicators could be established to determine the entitlement criteria for the grant awardees, as well as another set of indicators in determining the competitive criteria. The entitlement criteria could include indicators such as: percentage of renter occupied dwellings, percentage of homes built before 1939, percentage of renters with high energy cost burdens, median number of rooms, and percentage of households which use fuel oil for space heating.[4] The intent of structuring the program in this manner is to award grants to municipalities that have a demonstrated need to reduce energy consumption significantly across the residential sector, as well the capacity to implement energy efficiency retrofits.

6.2 Future Research

While this research was able to demonstrate some of the potential causes of variation in average household energy consumption for space heating, much

[4] Fuel oil refers to oil heat, which is generally more expensive than natural gas and more carbon-intensive.

more needs to be done to further examine the role of building age, tenure, and housing typology on energy consumption. A better understanding of the impact of building age, independent of tenure and housing typology is important to our understanding how this variables may influence energy consumption among and within municipalities. Future research examining the factors influencing residential energy consumption should include a larger sample, which would potentially allow for more variation among the building age variables.

There is a definite need for better understanding the role of tenure on household energy consumption. Future research efforts should be designed to specifically examine energy consumption among renter occupied dwellings, to better understand how building typology and age influence this variable.

6.3 Research Limitations

While this research was able to explain some of the variation in average household energy consumption for space heating, the findings are limited by the small sample size. Because our largest sample was only 56 municipalities it limited our ability to truly isolate the impact of specific variables. A larger dataset would have allowed for more variation and more significant findings. Furthermore, because not all the homes within the sample communities use natural gas for space heating, there is the potential that the independent variables were not entirely representative of the homes that use natural ga within those communities.

REFERENCES

Andrews, C.J. 2008. Greenhouse Gas Emissions Along and Urban Rural Gradient. *Journal of Environmental Planning and Management* 51 (6): 847-70.

Bamberger, L. 2010. Scaling the Nationwide Energy Retrofit of Affordable Multifamily Housing: Innovation and Policy Recommendations. *What Works Collaborative. <http://www.urban.org/publications/1001482.html>*

Brown, M.A., and F. Southworth. 2008. Mitigating Climate Change Through Green Building and Smart Growth. *Environment and Planning* 40: 653-75.

Brown, M.A., F. Southworth, and A. Sarzynski. 2009. "The Geography of Metropolitan Carbon Footprints." *Policy and Society* 27: 285-304.

Caldera, M., S.P. Corgnati, and Marco Fillippi. 2008. Energy Demand for Space Heating Through a Statistical Approach: Application to Residential Buildings . *Energy and Buildings* 40 (10): 1972-1988

Cervero, R. and M. Duncan. 2006. Which Reduces Vehicle Travel More: Jobs-Housing Balance or Retail-Mix Housing. *Journal of the American Planning Association* 72 (4)2006: 475-90.

Codoban, N. and C.A. Kennedy. 2008. Metabolism of Neighborhoods. *Journal of Urban Planning and Development* 134 (1): 21-31.

Dodman, D. 2009. Blaming Cities for Climate Change? An Analysis of Urban Greenhouse Gas Emissions Inventories. *Environment and Urbanization* 21: 185-201.

Ewing, R., K. Bartholomew, S. Winkelman, J. Walters, and D. Chen. *Growing Cooler: The Evidence on Urban Development and Climate Change* Washington, D.C.: Urban Land Institute, 2008.

Frank, L.D., S. Kavage, and B. Appleyard. 2007. The Urban Form and Climate Change Gamble. *Planning* 73 (8): 18-23.

Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, and D.J. Wuebbles. *Confronting Climate Change in The Northeast*. Publication. Cambridge, MA: Union of Concerned Scientists, 2007.

Hamin, E.M. and N. Gurran. 2009. "Urban Form and Climate Change: Balancing Adaptation and Mitigation in the U.S. and Australia." *Habitat International* 33: 238-45.

Holdren, N. 2005. Three Challenges for the Compact City as a Sustainable Urban Form, Household Consumption of Energy and Transport in Eight Residential Areas in the Greater Oslo Region. *Urban Studies* 42 (12): 2145-2166

Huang, YJ, and J. Broderick. 2000. A Bottom-Up Engineering Estimate of the Aggregate Heating and Cooling Loads of the Entire U.S. Building Stock. *Lawrence Berkeley National Laboratory* 1:1-16.

Hughes, Larry, K. Bohan, J. Good, and K. Jafapur. 2005. Calculating Residential Carbon Dioxide Emissions-A New Approach. *Energy Policy* 33: 1865-871.

ICLEI. *International Local Government GHG Emissions Analysis Protocol*. Tech. Vol. 1. Oakland: Local Governments for Sustainability, 2009.

Kavgic, M., A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic. 2010. A Review of Bottom-Up Building Stock Models for Energy Consumption in the Residential Sector. *Building and Environment* 45: 1683-1697

Kaza, N. 2010. Understanding the Spectrum of Residential Energy Consumption: A Quintile regression approach. *Energy Policy*. 38: 6574-6585

King County. Executive Office. *Seattle Climate Protection Initiative: Progress Report 2009*. Seattle: City of Seattle, 2009. Print.

Levinson, A., Nieman, S. 2004. Energy use by apartment tenants when landlords pay for utilities. (2004) *Resource and Energy Economics* 26, 51–75.

Levine, M., D. Ürge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling, H. Yoshino, 2007: Residential and commercial buildings. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Liao, H.C. and Chang, T.F. 2002. Space-heating and Water-heating Energy Demands of the Aged in the U.S. *Energy Economics* 24: 267-284.

Maruejols, L., Young, D. 2011. Split Incentives and Energy Efficiency in Canadian Multi-Family Dwelings. *Energy Policy* 39: 3655-3668

Massachusetts Department of Environmental Protection. Executive Office of Energy and Environmental Affairs. *Statewide Greenhouse Gas Emissions Level: 1990 Baseline and 2020 Business As Usual Projection*. Boston: Commonwealth of Massachusetts, 2009.

Meir, H. and K. Rehdanz. 2010. Determinants of Residential Space Heating Expenditures in Great Britain. *Energy Economics* 32: 949-959.

Mumford, L. *The City in History*. New York: Harcourt, Brace and World, 1961.

Santin, O.G. Itard, L., and Visscher, H. 2009. The Effect of Occupancy and Building Characteristics on Energy Use in Space and Water Heating in the Dutch Residential Stock. Energy and Buildings 41: 1223-1232.

Staley, S., 2008. Missing the forest through the trees? Comment on Reid Ewing and Fang Rong's the Impact of Urban Form on US Residential Energy Use. *Housing Policy Debate* 19 (1): 31–43.

Swan, L.G., and V. I. Ugursal. 2009. Modeling of End-user Consumption in the Residential Sector: A Review of Modeling Techniques. *Renewable and Sustainable Energy Reviews* 13: 1819-835.

Tommerup, H., Svendsen, S. 2006. Energy Savings in Danish Residential Building Stock. *Energy and Buildings* 38: 618-26

Vadas, Timothy et al. 2007. Approaches for Analyzing Local Carbon Mitigation Strategies: Tompkins County New York, USA. *International Journal of Greenhouse Gas Control* I: 360-73.

VandeWeghe, J.R. and C. Kennedy. 2007. Spatial Analysis of Residential Greenhouse Gas Emissions in the Toronto Census Metropolitan Area. *Journal of Industrial Ecology* 11(2): 133-144.

Wheeler, S.M. 2008. State and Municipal Climate Change Plans. *Journal of the American Planning Association* 74(4): 481-96.

Whyte, William H. *The Last Landscape*. Philadelphia: University of Pennsylvania. Print.