THE IMPACT OF URBAN FORM AND HOUSING CHARACTERISTICS ON RESIDENTIAL ENERGY USE

A Dissertation

by

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ABSTRACT

Cities and their characteristics of energy use play an important role in climate change. While there is abundant research about the impact of energy use on transportation the impact of urban form and housing characteristics on residential energy use has not been considered widely. There is certainly a need to take a closer look about the residential energy use and housing relationships to identify planning implications.

This study examines the relationship between various urban form, housing characteristics and the energy use that result from residential electricity and fuel use. Ordinary least squares regression methods are used to measure the correlations between energy consumption and variables describing housing and urban form characteristics in the metropolitan statistical areas in the United States.

After controlling for differences in energy price and income, a positive relationship between residential energy consumption and a history of greater rates of land conversion was found. This study also finds significantly higher energy use associated with a greater incidence of detached single-family housing when compared against high-rise buildings. A correlation between increased rate of row housing and lower energy use was found as well.

This study can contribute to a literature that can help planners to create more environmentally- friendly cities by contributing to the understanding of the impacts that certain energy- related housing characteristics have on the sustainability of a city. The literature regarding smart growth and new urbanism should explore potential impacts on

household energy consumption in its discussion of urban planning along with considering impacts on transportation related energy use.

DEDICATION

To my parents

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NOMENCLATURE

MSA	Metropolitan Statistical Area
BTU	British thermal unit
RECS	Residential Energy Consumption Survey
VMT	Vehicle Miles Traveled
ACS	American Community Survey
OLS	Ordinary Least Square

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CHAPTER I

INTRODUCTION

1.1 Background; Energy and Planning

The dynamic interaction between energy systems and the spatial organization of society has been a subject of considerable interest (Ashworth, 1974; Owens, 1986). At all levels of spatial structure, and land-use patterns in part determine levels of energy consumption. There has been many debates regarding the integration of energy issues in planning process but little has been succeeded yet (Ashworth, 1974; Clark & Dickson, 2003; Owens, 1990). There is certainly a need to take a closer look what we know about the energy and land use relationship to identify clearly its planning implications (Clark & Dickson, 2003).

The cyclical relationship of energy system and spatial structure is represented schematically in figure 1. In reality, it is far from being so clearly defined; cause and effect are often difficult to distinguish and many aspects are not quantified yet. Statistics are usually available only at national level, even though energy budgets differ quite markedly on a smaller geographical scale and the potential for conservation and use of renewable sources is likely to show up more clearly in a localized analysis(Rickwood, Glazebrook, & Searle, 2008; Wilbanks, 1981).

The nature and availability of energy sources clearly influence the spatial structure of society. Historically, energy transitions-from the use of dispersed organic sources, through wind and water power, to large-scale exploitation of fossil fuels-can readily be in the concentration of most of the population of developed countries into urban centers. In short, there is simple ample evidence that energy supply, price and distribution among the important factors shaping urban and regional systems, even if the relationship is indirect and complex(Owens, 1986).

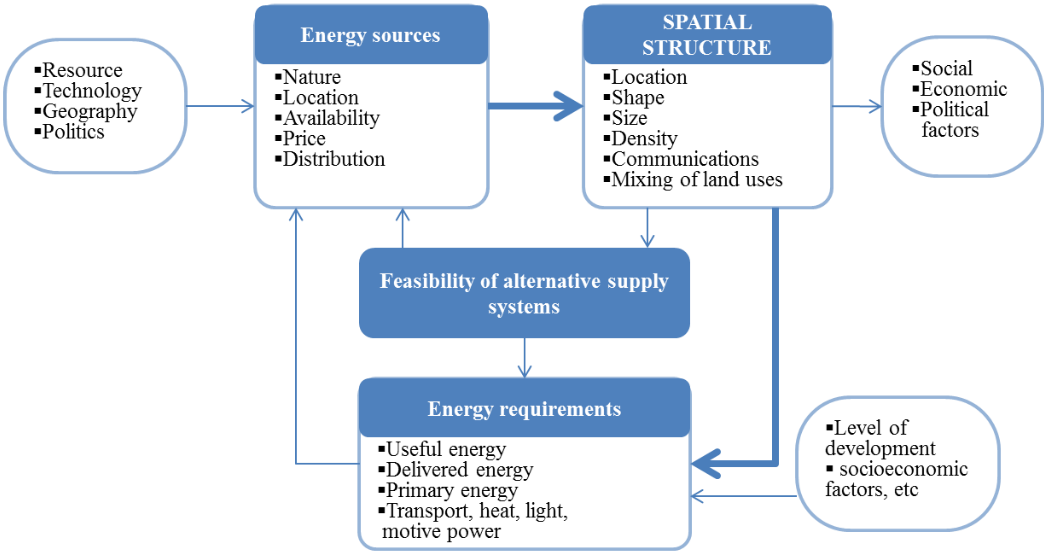

Figure 1 The Relationship between the Energy System and Spatial Structure.

The influence of energy on urban form is only one aspect of the relationship. Once in place, land-use patterns and the built environment interact with the energy systems in two important ways. First, they are among the determinants of the level and pattern of energy demand. Spatial structure influences energy requirements for various activities, especially transport and space heating, which account for well over the half of delivered energy needs1. In low-density suburbs, for example, segregated from

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[1] Measure of the amount of energy arriving at a site or building

employment and services, and poorly served by public transport, people are necessarily dependent on a high level of personal mobility, and their travel patterns are inevitably ‘energy intensive’. Second, spatial structure is an important determinant of the feasibility of future alternative systems for energy supply and distribution, such as combined heat and power generation or the exploitation of ambient energy sources, which have particular requirements in terms of density, layout, and orientation. Different aspects of spatial structure become important at different scales, from the regional, where the broad pattern of settlements is significant, to the local, where what matters is in relation to microclimate, layout, and orientation. These structural variables are categorized by scale in figure 2.

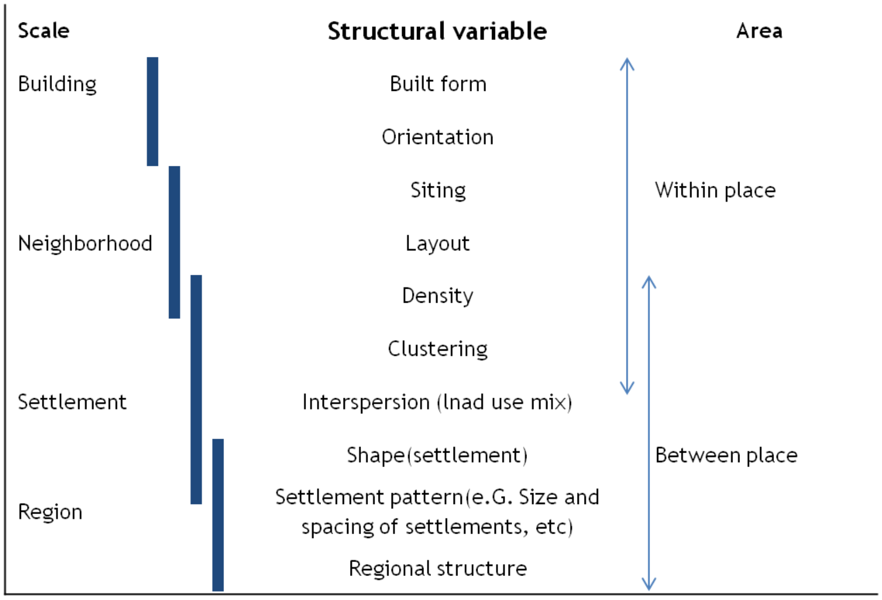

Figure 2 Significant Structural Variables at Different Scales.

1.2 Research Problem

The meaning of sustainability has various aspects, with many implications in different fields. However, there is not yet any consensus in our daily lives. How to reduce our energy demand and therefore related greenhouse gases emission and pollution is one of the critical concerns accompanying sustainability of a city. Climate change is a critical issue with significant negative impacts on not only the natural environment, but human life and future of our society as well. Research shows that climate change presents serious global damages and an urgent solution is needed. Around the world, rising temperatures are shifting entire ecosystems, disrupting the environment on which billions of people depend. Our energy use patterns and associated emission and pollution in cities across the globe could be both the cause and key to reducing climate change’s negative effects.

Cities and their characteristics of energy use play an important role in this situation. They also represent an important focus of any effective solution. The number of people in the world who live in urbanized areas exceeded 50% of the global population for the first time in history in 2007 (United Nations Population Fund, 2007). This represents the importance of cities. According to the United Nations Population Division, no more than 30% of the world’s population lived in cities in the year 1950. By the year 2025, however, the figure is projected to reach 60% and will continue growing. The United States is even more urbanized: as of 2005 fully two thirds of its population lived in the 100 largest cities alone (U.S. Census, 2009).

Crucial issues about how to design or renew cities and about how to manage housing confront planners across the country now and will only increase in importance and urgency in to the future. In addition to the trend toward urbanized living, the United States is expecting a huge expansion in population. According to the 2008 projections by the Census Bureau, almost 140 million additional people would live in urbanized area in just the next 40 years. In the next 50 years, the U.S. will likely build new housing equivalent to 70% of the existing housing stock (Brown & Southworth, 2006).

However, the research about the urban form and energy use is unbalanced in that. The impact of spatial structure on residential energy consumption has not been studied extensively while there is abundant research about the impact of urban form on transportation related energy use. Most of the research has looked at how city design affects vehicle miles travelled, and therefore affects total transportation energy consumption and related emissions. Less attention appears to have been paid to how urban form characteristics, such as density and land use, affect residential energy consumption(Bento, Cropper, Mobarak, & Vinha, 2005; Boarnet & Sarmiento, 1998).

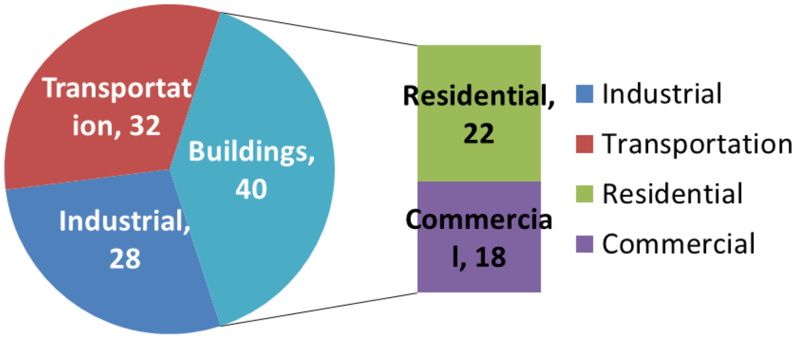

Figure 3 Energy Consumption by Sector
Source: Energy Information Administration (2005)

As shown in figure 3, the residential sector explains 22% of the U.S. total energy consumption when transportation sector explains the 28% of the annual U.S. energy consumption (Energy Information Administration, 2005).

The energy use by the residential sector is also a significant long tern threat to the environment. This sector consumes nearly as much energy and produces nearly as much greenhouse gas emissions as the transportation sector. Considering that past studies have found relationships between urban form and energy use, the association between urban structure and residential energy use needs more investigation(Ewing, Cervero, Nelson, & Niles, 2001; Ewing, 2008; Harwood, 1977; Newman & Kenworthy, 1989).

Planners' approach to sustainable urban growth is similarly unbalanced. Much has been said during the past decade about energy considerations into the urban planning area but relatively little has been achieved. There is certainly a need to look at the experience of energy integrated planning to date. Planning sector tend to focus on improving the energy efficiency of existing housing stock, pushing new more efficient technologies and improving consumer information about energy use (Turner, Wial, & Wolman, 2008). However even though efficiency standards have been tightening and new technology has been developed, total energy use is still growing (Kaza, 2010; Perez-Lombard, Ortiz, & Pout, 2008). The impact of local planning, such as changing residential density regulation and the housing-type guide lines on residential energy consumption, need more investigation.

It seems likely that the problem of high residential energy consumption cannot be solved only with increasing energy efficiency. Demand side measures will be required, and strategies to reduce residential energy use will be needed.

The research proposed here in would examine the influence of urban form and housing characteristics on residential energy consumption. The goal is to measure the relative impacts on residential energy use of different characteristics of urban housing stock, in order to learn more about which options present the most compelling opportunities for planners to reduce a city's carbon footprint. This study evaluates these questions in the U.S. context, utilizing data on the 100 largest metropolitan areas. Information about the relative impacts of various housing and sprawl factors on energy consumption would give planners knowledge of whether it is more effective to create incentives for developers to build on already-used land or to create incentives for energy-efficiency of existing homes improvements. By contributing to the understanding of the degree of the impacts that certain energy- related housing characteristics have on the sustainability of a city, this study can contribute to a literature that can help planners create more environmentally- friendly cities.

Cities cover less than 1 percent of the Earth's surface and are generally more energy-efficient than rural areas, but they're still insatiable for fuel and electricity because so many people live in them. They're often blamed for 75 percent of global energy consumption and greenhouse gas emissions, and while some researchers have challenged those figures most could still vastly benefit from some upgrades(Brown &

Logan, 2008). And with metro areas around the United States expecting continued growth in the near future, many are examining how efficiently they use energy.

Cities in the U.S. have power to greatly impact climate change(Jenks & Jones, 2010; Owens, 1986). For instance, decisions on city design, population density, modes of travel within and even between communities all lie under the control of local planners. As cities grow and the country becomes an even more urbanized, cities and their characteristics of energy use will play more important role in climate change. Brown and Logan studied residential energy use and carbon emissions in US metro areas to examine how certain characteristics of residential communities. This allows an opportunity to develop an understanding through further study of these data of how various urban planning decisions can impact future demand for residential energy, and then to take long-term consumption into account when deciding what building-code standards to adopt, how to zone new land for development, or where to encourage or discourage development. While some researches(Ewing & Rong, 2008) examined correlations with some types of housing and made use of some of the census data this analysis will use, this study will examine the data from the 100 largest metropolitan areas in the United States in 2005 in ways the prior analysis did not: it will look more closely at a greater subdivision of housing stock to improve the understanding of the effects of housing type on emissions from household energy use, and it will use various regression analysis to take a broader look at the relative impacts of planning options related to housing, energy supply, and urban form.

1.3 Research Objectives

The general objective of this research is to understand the characteristic of physical urban structures and related energy consumption. Specifically, this research proposes to examine the influence of urban form attributes of residential energy consumption. How do our cities consume energy? To what extent does single housing correspond to higher household related emissions than various categories of attached housing? Are rented apartments associated with higher emissions than owned homes? Does sprawled urban form have higher or lower associated household-based emissions? This study evaluates these questions in the U.S. context, utilizing data on the 100 largest metropolitan areas. Information about the relative impacts of various housing and sprawl factors on energy consumption would give planners knowledge of whether it is more effective to create incentives for developers to build on already-used land or more effective to create incentives for home energy-efficiency improvements.

By contributing to the understanding of the degree of the impacts that certain energy- related housing characteristics have on the sustainability of a city, this study can contribute to a literature that can help planners create more environmentally- friendly cities.

1.4 Organization of the Dissertation

This dissertation consists of five chapters. Chapter I introduces the background of the study and research aims. Chapter II reviews literature relevant to this research. First it discusses the overall concept of energy, spatial structure, and planning. Chapter

II organizes the literature review into: 1) research on residential energy consumption, 2) relationships among the urban form characteristics and energy use, 3) relationships among housing characteristics and energy use. Chapter III consists of the conceptual framework, research hypotheses, and research flow and design. Chapter III also identifies the research area, data sources, and the methodology used for testing the hypothesis. Chapter IV reports the results of the analysis. Analysis discovered the effects of various factors on the residential energy consumption patterns in U.S. metropolitan areas. Chapter IV also demonstrates the trends and distribution of household energy consumption. Finally, Chapter V states the significant findings of the study, discussion and conclusions based on the findings, study limitations and recommendations for future research.

CHAPTER II

LITERATURE REVIEW

This chapter reviews literature related to this research. This chapter organizes the literature review into: 1) relationships among the urban form characteristics and energy use, 2) relationships among the housing characteristics and energy use, 3) research on residential energy consumption.

2.1. Urban Form Characteristics

The effect of urban form on residential energy consumption is a new area of inquiry. Urban form is a subject earning significant attention. This field, comprised of the "new urbanism" and "smart growth" movements, seeks to achieve denser, more walkable communities with short distances between home, school, work, commercial areas, and public services. Those benefits include lower obesity, better community cohesion, greatly reduced emissions from transportation, shorter commuting times to work and school, and a number of other life-improving outcomes. (See www.smartgrowthamerica.org and www.newurbanism.org.)

Bulk of research support the idea that urban form affects energy consumption and more dispersed forms increase per capita energy use(Hawkes, Open University. Centre for Configurational Studies., & Martin Centre for Architectural and Urban Studies., 1987; Newman, Kenworthy, Williams, & Burton, 2000). Research on urban form and energy has considered its effect on the amount of vehicle travel that urban form requires by traveling. People in low-density communities where housing is separated from other land uses have to drive more to get to where they need to be(Cervero & Murakami, 2010). Also, they tend to drive, rather than walk, and so the energy intensity of transportation rises even faster as more trips are in vehicles(Frank et al., 2006).

The literature regarding the urban form has been recognized several urban sprawl phenomenon (Brownstone & Golob, 2009; Diamantini & Vettorato, 2011; Freilich, Sitkowski, & Mennillo, 2010; Jenks, Kozak, & Takkanon, 2008; Norman & MacLean, 2006). The population density has been the most popular measures in most of research. The proportion of the population who live in central district also got the most attention as the measure of the urban form characteristic.

Pendall (1999) established sprawl as the change in a city's population density over time in a study of sprawl, land use values, and metropolitan governance. In seeking to measure the influence of sprawl on affordable housing and the distribution of urban population by race, Kahn (2000) quantified sprawl through measuring the proportion of employment situated more than 10 miles from the downtown district of large US cities.

Burchell (2005) categorized four spatial dimensions of sprawl as density, land use, centrality and connectivity). However, it is hard to represent all these spatial dimensions in a single indicator of urban form. As argued by Ewing et al. (2003), “sprawl is a complex phenomenon that can be effectively measured through quantifying several dimensions of urban form.”

Considering this observation, Ewing et al. (2002) developed a composite index of sprawl based on four measures of urban form: centeredness, connectivity, density, and land use mix. Ewing employed data from the U.S. Census Bureau, the American Housing Survey, and U.S. Department of Agriculture, among other sources, to develop a cohesive measure of urban sprawl through principal components analysis. Ewing et al.'s county sprawl index have been widely used in sprawl-related research and have been validated in terms of expected outcomes (Ewing et al., 2002, 2003; Ewing & Rong, 2008; Kahn, 2006). As this index has been found to be a useful metric for measuring urban form, Stone (2008) employed the Ewing et al. data for 45 major US cities to assess the influence of sprawl on air quality.

Characteristics to measure the urban form in the previous literature are represented in table 1. Still, literature suggests that the net impact on urban form on people's demand for housing is ambiguous and calls for empirical analysis.

Table 1 Characteristics to Measure the Urban Form

Characteristics	***Measurement detail***	***Data Source***
Density	Gross Population Density in persons per square mile	US Census
	Percentage of population living at densities less than 1,500 persons per square mile(low suburban density)	US Census
	Percentage of population living at densities greater than 12,500 persons per square mile (urban density)	US Census
	Estimated density at the center of the metro area	US Census
	Gross population density of urban lands	USDA
	Weighted average lot size for single family dwellings (in square feet)	American housing Survey
	Weighted density of all population centers within a metro area	Claritas Corporation
Land use mix	Percentage of residents with businesses or Homes, Shops and Offices institutions within 1/2 block of their homes	American Housing Survey
	Percentage of residents with satisfactory neighborhood shopping within 1 mile	American Housing Survey
	Percentage of residents with a public elementary school within 1 mile	American Housing Survey
	Balance of jobs to residents	Census Transportation Planning Package
	Balance of population serving jobs to Census Transportation residents. Population serving jobs include Planning Package retail, personal services, entertainment, health, education, and professional services	Census Transportation Planning Package
Centrality	Variation of population density by census Centers tract	US Census
	Rate of decline in density from center (density gradient)	US Census
	Percentage of population living within 3 miles of the central business district	Edward Glaeser, Brookings Institution
	Percent of the population living more than 10 miles from the CBD	Edward Glaeser, Brookings Institution
	Percentage of the population relating to centers within the same metropolitan statistical area	Claritas
	Ratio of population density to the highest density center in the metro area	Claritas
Accessibility	Average block length in urbanized portion of the metro area	Census TIGER files
	Average block size in square miles	Census TIGER files
	Percentage of small blocks	Census TIGER files

Table adapted and modified from Ewing (2003).

2.2. Housing Characteristics

The research on the impact of housing type and density on housing energy use has mostly been done recently. Housing characteristics can affect energy consumption by housing size, housing type, density, building material, built year and building orientation(Holden & Norland, 2005; Holloway & Bunker, 2006; Kaza, 2010; Peiser, 2001). It has been suggested that low density development and increasing number of energy consuming appliances have contributed to rapid increase in energy consumption, even though efficiency standards have been tightening (Kaza, 2010). Most of the research in residential energy has been interested in the effect of particular policies, such as weatherization programs and energy standards(Berry, 2003; Brown & Southworth, 2006).

Single family detached housing (SFD) is the major housing type in the US. According to U.S. Department of Housing and U.S. Census Bureau, single family detached housing accounts for over 64% of the total housing stock in 2008 (U.S. Census Bureau, 2008). Kahn (2000) used residential energy-use data to compare energy consumption in the home by urban households and suburban households, and found no significant difference between the two. Ewing, Pendall and Chen (2002) took issue with Kahn’s categorization of urban and suburban, arguing that a poorly-defined categorization of urban form leads to the comparison of fundamentally similar groups with only superficial distinctions. Reid Ewing and Fang Rong (2008) make the case for the importance of sprawl’s effect on household energy use and carbon emissions, pointing out that total household energy consumption rivals total transportation energy consumption, both in scale and in carbon emissions. The authors use data developed by the Energy Information Administration (EIA) on energy use by end-use sector to argue this point of scale. By that measure, EIA data actually show transportation to represent about 30% greater total energy uses.

Ewing and Rong (2008) found that energy consumption in households goes up with incomes, goes down with energy prices, and varies by the ethnicity of the occupants. After controlling for those and other factors, they found a strong relationship between housing type and energy consumption. Single-family detached housing used far more energy (over 50% more for heating, and 26% more for cooling) than comparable homes in multi-unit buildings. Larger homes, as measured by heated and cooled square footage, used significantly more energy than comparable smaller homes. Ewing and Rong (2008) argued that compact urban forms have substantial energy savings. Using a variety of data sources and methods, they suggest that most of the energy savings are realized because of increase in density and changes in housing type mix. In their conclusion, Ewing and Rong (2008) argue that pursuing compact development can save almost as much household energy use as it can in transportation energy use.

Holden and Norland (2005) argue that in Oslo, Norway, controlling for the age of the house, the effect of housing type on energy conservation is largely negligible after 1980. Nevertheless, the prevailing wisdom is that non-Single Family Detached housing types have energy savings because of shared walls and floors.

However, Randolph (2008) argues that substantial reduction in energy consumption is possible due to energy efficiency improvements rather than due to changing density or housing type. Furthermore, he argues that much of energy savings in compact developments are realized due to changes in travel patterns rather than changing building energy consumption patterns. Randolph (2008) questions the soundness of the regressions in Ewing and Rong's (2008) analysis. Randolph's concerns are with the quality of the data used, as well as the methodology that Ewing and Rong used to combine four different data sources and then to generate results. He finds their results untrustworthy and their methodology both unclear and unpersuasive. He disputes that compact urban form can induce reductions from household energy use that would be on par with the reductions they induced from reduced vehicle mile travel (VMT). He also disputes what he perceives as a misrepresentation of the relative importance of energy-efficiency measures for cutting household energy use. Holloway and Bunker (2006), using a survey approach, found that most of the emissions differences between urban and suburban communities came in the form of increased auto use in the suburbs. However, their research was focused on six selected communities in or near Sydney, while Ewing and Rong (2008) were using national household-level data sets in the United States.

However, Norman, MacLean and Kennedy (2006) also argued that most of the benefit of denser urbanized communities would come in the form of reduced emissions from auto use. The implication for policy, from their point of view, was that efforts to develop and urbanize in sustainable ways should focus primarily on reducing vehicle miles traveled. Their work relied on two case studies of communities in Toronto.

Indeed, there is not yet any consensus in the literature as to the magnitude of the difference in energy use between multi-family housing structures and detached single-family homes. A case study by Vieira and Parker (1991) at the University of Central Florida found that average energy use in detached houses in that state was 85% to 99% higher than the average energy use in attached buildings, when controlling for differences in occupancy.

The Department of Energy’s Energy Information Administration (1991), however, produced a different result: its analysis of data from 1984, 1987 and 1990 showed that detached single-family homes used roughly 18-20% more energy than multi-unit homes, but used nearly 80% more than housing units in large buildings with more than five units. While the EIA adjusted its figures for weather, it did not adjust for differences in square footage, income, or other controls that are often part of the comparison in other studies. Apartments in multi-unit buildings have a smaller median room count and the median incomes for their occupants are lower in all 100 MSAs according to the Census Bureau’s American Community Survey, so these results are likely overestimating the true impact of housing type on energy use.

As yet, only one study has been done on housing energy use with the benefit of the recently-developed collection of energy-use and emissions data from the 100 largest metropolitan statistical areas (Brown & Logan, 2008). The presence of such a collection of data, measured at the same time and by the same methodology, opens up new opportunities to look at the impacts of urban form in a systematic way that produce reliable results that can inform discussions in communities around the country and potentially around the world. This is preferable to simply adding more isolated case studies to the literature, and preferable also to national-level analyses that cannot incorporate the differences between and among various communities.

2.3. Previous Energy Consumption Research

There are few examples of contemporary research which attempt to analyze the relationship between urban planning and both transport and residential energy, to a comprehensive analysis. Research relate to residential energy consumption varies by scale and measurement types (Hirst, Goeltz, & Carney, 1982; Kahn, 2000; Newman & Kenworthy, 1989).

Newman and Kenworthy (1989) measured gasoline use (gallon per capita) to measure the individual transport energy consumption. Troy (2003) used life cycle analysis to calculate the total transport and housing energy and emissions from a sample of 41 households in apartment buildings in the city centre of Adelaide, Australia and compare them with suburban households. Troy (2003) suggests that embodied energy consumption may be more significant than directly measured energy. Reid Ewing and Fang Rong (2008) used data developed by the Energy Information Administration on energy use by end-use sector. The basic unit of analysis in this study is the individual household.

Table 2 shows how previous research measured residential energy by measurement unit and data type. The data type varies according to the study site scale. The reliance on the secondary data is inevitable in the regional scale research (Baynes, Lenzen, Steinberger, & Bai, 2011; Lenzen, Dey, & Foran, 2004; Norman MacLean, & Kennedy, 2006).

Table 2 Previous Literature Relate to Energy Use

Author	***year***	***Measurement unit***	***Data type***	***Energy type***	***Scale***	***Study site***	***Study type***
Hirst et al.	1982	Btu, cost($)	secondary (1979NIECS)	operational energy	household	U.S.	cross-sectional
Newman and Kenworthy	1989	gasoline use (gallons per capita)	primary	Operational transport energy	individual	international	cross-sectional
Branadon	1999	kWh hours	primary	operational energy	local	Bath,UA	longitudinal
Kahn	2000	annual household miles driven(miles),Btu	secondary (1995NPTS, 1993RECS)	operational transport energy	household	U.S.	cross-sectional
Boarnet and Crane	2001	VMT	primary	transportation energy	household	U.S.	cross-sectional
Troy et al.	2003	kilowatt-hours	secondary	direct embodied +transportation	household	Adelaide, Australia	cross-sectional
Holden	2005	kWh hours	primary	operational energy	individual	Oslo, Norway	cross-sectional
Bunker et al.	2005	GJ/capita/year	primary	operational energy	household	Sydney	cross-sectional
Norman et al.	2006	PJ petajoule (1 million gigajoules)	Secondary (CREEDAC 2000 NRCan 2003)	direct embodied +transportation	household	Toronto, Canada	cross-sectional

Table 2 Continued

Author	***year***	***Measurement unit***	***Data type***	***Energy type***	***Scale***	***Study site***	***Study type***
Dey et al.	2007	GJ/capita/year	secondary (from local statistics)	direct + embodied	household	Melbourne, Australia	cross-sectional
Reid Ewing et al.	2008	Btu	secondary (2001RECS)	operational energy	household	U.S Cities	cross-sectional
Randolph	2008	MBTU/year, kWh/year	primary	operational energy	household	U.S. Cities	cross-sectional
Brown and Logan	2008	Btu	secondary (platts analytics)	operational	county-level	100 metropolitan U.S.	longitudinal
Baynes et Bai	2009	GJ/capita/year	secondary (from regional data)	direct + embodied	household	Melbourne, Australia	cross-sectional
Perkins et al.	2009	GJ/capita/year	primary +secondary	direct embodied +transportation	household(apartment)	Adelaide, Australia	cross-sectional
Baynes et al.	2011	GJ/capita/year	secondary (from local statistics)	direct + embodied	household	Melbourne, Australia	cross-sectional

CHAPTER III

RESEARCH METHOD AND DATA

3.1 Conceptual Model and Hypothesis

The fundamental idea of this research is based on the fact that urban form and housing characteristics can be linked with city's energy consumption and following carbon emission and climate change. In order to develop the conceptual framework, this research focused on spatial structural factors collected from a literature review of previous studies. The factors include urban form characteristics, housing characteristics and socioeconomic and demographic factors such as income and fuel price. The conceptual framework for this research is shown in Figure 4.

The hypothesis underlying this analysis is that communities with characteristics of greater density will show significantly lower per-capita household energy use from their residents than will communities with characteristics of sprawl.

This research will focus on two different but parallel models, both attempting to measure the correlation of several characteristics of housing and indicators of urban form with variations in the per-capita household energy consumption, measured for each metropolitan statistical area. The first model is a smaller model with a simpler expression of housing stock that allows for a comparison of effects across two different years, 2000 and 2005. The second model, utilizing data available only in 2005, examines housing stock in more detail, breaking multi-unit housing into several subcategories using data that are not available in the year 2000.Using an ordinary least squares regression and data from the 100 largest metropolitan statistical areas in the United States, this analysis seeks to measure whether how much these characteristics correspond to decreases in energy use.

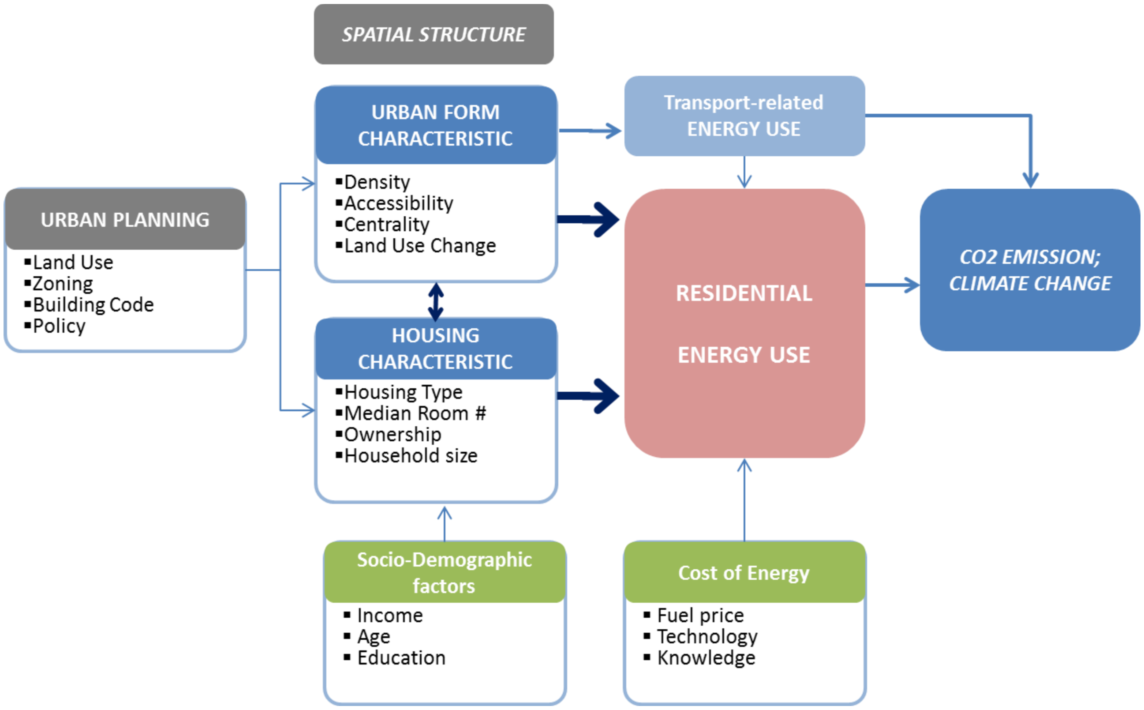

Figure 4 Conceptual Framework

3.2 Study Areas

This study investigates metropolitan statistical areas in the United States. Figure 5 shows the 100 largest U.S. metropolitan areas. Cities and their characteristics plays significant role in energy consumption. According to the United Nations Population Division, no more than 30% of the world’s population lived in cities in the year 1950.

By the year 2025, however, the figure is projected to reach 60% and will continue growing. The United States is even more urbanized: as of 2005 fully two thirds of its population lived in the 100 largest cities alone (United Nation Population Division, 2011). This represents the importance of cities.

Figure 5 Study Area

Urban cores are accountable for a most of the nation's energy use and greenhouse gas emissions. Almost two-thirds of the U.S. population live in the nation's largest 100 metropolitan areas (Brown & Logan, 2008). For these reasons, metropolitan areas need to be more considered to solve the problem of the energy crisis and climate change challenge.

A Metropolitan Statistical Area is defined as one or more adjacent counties or county equivalents that have at least one urban core area of at least 50,000 populations by the United States Office of Management and Budget. This research investigates the energy consumed by the 100 largest U.S. metropolitan areas[2] to characterize metropolitan contributions to energy consumption.

3.3 Variables

3.3.1. Independent Variables

The independent variables in this study fall into several categories: 1) Variables relating to Housing characteristic, 2) Variables relating to urban form, 3) Variables relating to the cost of energy and 4) Control variables.

Variables Relating to Housing Characteristic

Various types of housing are included in this model, expressed as a percentage of total housing. These include detached single-family homes, duplexes, homes in buildings of three to four units, homes in buildings of five to nine units, homes in buildings of ten to nineteen units, and homes in buildings of twenty or more units. For the comparison model, housing type is measured by the percentage of housing in multi-unit structures.

Some of the variables impact energy use directly, while others only do so indirectly. Multi-unit housing is expected to impact energy use in two ways. First, the presence of attached housing involves shared walls and a relatively small amount of surface area in proportion to the total living space. Only some of the wall and ceiling

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[2] See Appendix A for the list of 100 largest U.S. Metropolitan Statistical Areas.

area of these housing units faces the outside of the building for these units, while all of the wall and ceiling area faces the outside for detached single-family housing. This should reduce the heating and cooling losses due to the temperature differential from outside to inside the structure. Second, homes in multi-unit buildings often share heating and cooling systems, which might reap efficiencies over the operation of individual units for each home.

Median room size is also included to represent housing characteristic. The median number of rooms in each city should vary positively with average housing size, and therefore should correspond positively with energy use and greenhouse gas emissions. This study expects this relationship because the median number of rooms should correlate with average housing size. The housing size affects energy conservation directly(Clark & Berry, 1995; Kaza, 2010)

Variables Relating to Urban Form

This model includes the number of housing units per square mile, the rate at which rural land was converted for new homes from 1980 to 2000, weighted by how much of the housing stock was built during that time. The per-capita emissions from highway traffic within each MSA is also included here as an instrument for sprawl because of the strong linkage between urban sprawl and increase in VMT.

Low housing density per square mile, as well as a history of converting a lot of land for relatively few new houses, should drive up energy use, but this impact will be indirect. I do not think that the distance between one house and the next that would have a direct impact on either home's energy use, but I expect that a relatively high density of homes per square mile should have the effect of constraining housing design in ways that reduce their energy demand. First, if lots are smaller, houses are more likely to be smaller themselves – and fewer square feet are strongly correlated to less energy consumption in the literature. Further, they are more likely to be spatially compact. For example, a two-story house with a basement will tend to have a smaller surface area and fewer windows than a sprawling ranch house that contains the same amount of inside space. Marginal changes in these values should have larger effects on energy use and emissions where housing is already dense, but smaller effects where housing is broadly spaced. Adding an additional house to a block filled with small lots and small homes would likely pressure those homes and lots to be smaller still, while adding an additional house to an area where each house sits on three acres is unlikely to constrain the size or shape of the other houses. Therefore both of these variables are modeled in quadratic form.

Because the literature on sprawl has established a link between using urban form and emissions from car travel, it is valid to include per-capita auto emissions as an instrument for sprawl. The research to this point has not yet generated a consensus around any particular operational model for urban sprawl (Ewing et al., 2002; Ewing, 2008), and it is appropriate to include a variable that measures a central component of the concept of sprawl, even if that variable is not strictly a housing or building characteristic.

Variables Relating to the Cost of Energy

Consumers are confronted with the costs of energy in different ways. An energy price per unit of energy measured in cents per kilowatt-hour is included, and also a variable expressing the proportion of apartments in which the utility bills are included in the rent. The utility-bills variable is weighted by the inverse of the home ownership rate because a high percentage of included utilities in a city that had a tiny apartment population would otherwise show a misleadingly small effect from that variable.

Consumers of energy are expected to be sensitive to the prices they face. Therefore it is expected that higher energy prices will drive down energy consumption, while higher incomes will drive energy consumption upward. Along these lines, a higher proportion of apartments in which the landlord pays the utilities will drive energy consumption up, because the resident in that case does not face a marginal cost of consuming additional energy, and so is more likely to consume it freely(Levinson & Niemann, 2004; Munley, Taylor, & Formby, 1990). All factors mentioned here are expected on the energy used by residents in these communities.

Control Variables

Various factors outside the field of urban design and outside the reach of urban planning are recognized to have a large impact on household energy use and on carbon emissions(Eto, 1988; Quayle & Diaz, 1980). These include per-capita income, the percentage of homes that are owned rather than rented, the natural logs of total heating and cooling degree-days for the year in question, and regional dummy variables to express the geographic location of communities around the country(Holden & Linnerud, 2010; Sivak, 2009). These factors are included in the model, in order to control for their impact and avoid allowing them to distort the observed effects of the variables of interest.

3.3.2. Dependent Variables

The dependent variable in this study is annual per capita energy use from residential electricity and fuel consumption. The data regarding household energy use were obtained from a working paper by Brown and Logan (2008), “the residential energy and carbon footprints of the 100 largest U.S. metropolitan areas.” From this paper, this study obtained estimates on per capita household energy consumption for 2005 and 2000. It is problematic to obtain publicly accessible national data for residential energy use at metropolitan level. Most U.S. building and appliance energy-efficiency analyses are based on The Residential Energy Consumption Survey (RECS) and Commercial Building Energy Consumption Survey (CBECS) (Brown & Logan, 2008). However, the sample size are not big enough to metropolitan area scale to produce reliable assessments results (Brown & Southworth, 2006; Brown, Southworth, & Sarzynski, 2008). Because of this lack of publicly available electricity and fuel consumption data, data for this analysis were compiled from several sources. Brown and

Logan obtained energy consumption data from Platts Analytics[3] that could be aggregated by ZIP code. The data was supplemented with state-level data provided by EIA.

3.4 Data

Data for this analysis were collected from several sources. The household energy use data is obtained from a working paper, entitled, “The Residential Energy and Carbon Footprints of the 100 Largest U.S. Metropolitan Areas” (Brown & Logan, 2008). From this paper, this study developed estimates on per-capita annual energy use from residential electricity and fuel consumption in 2000 and 2005.

To estimate energy use from electricity use, the authors of the report relied on a database developed by Platts Analytics, which assembled estimates of total energy sold by all utilities to customers within each of the 100 largest metropolitan areas. Platts collects these data, as well as the data regarding the number of customers buying from each utility, annually from the mandatory filings that each energy supplier must submit to the Federal Energy Regulatory Commission. The authors used these data to first estimate per-household energy use at the zip-code and county levels within each MSA, and then adjusted that data to account for household characteristics such as the number of people per home and the percentage of housing in which landlords pay utilities. Once adjusted, the authors summed the county data to produce energy-consumption estimates from electricity for entire metropolitan statistical areas. Brown and Logan (2008) derived carbon emissions from electricity consumption using data regarding emissions

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[3] http://www.platts.com

intensity for each metropolitan area, reported for 2000 and 2005 in the EIA's Annual Energy Outlook reports for 2002 and 2007, respectively. However, this study only considered energy consumption data.

To estimate the energy use from the use of other fuels, such as natural gas, heating oil or biomass sources, and the authors relied on state-level data for average consumption rates of fuel, divided by types of housing. Using census records to obtain numbers of housing type for counties within each MSA, they weighted the household averages for each housing type by the number of each housing type within each county, and generated a per-household and total energy use from fuels for each county. To generate estimates for carbon emissions, they derived fuel volumes from the energy-use values they had developed, and multiplied the fuel amounts by carbon content coefficients established by the EPA. The value this study adopted for household energy use is the sum of the electricity use and for fuels use from Brown and Logan (2008).

For a measure of vehicle related energy use in each MSA, this study relies on estimates created in another working paper from the Brookings Institution. This time, the data were drawn from a paper, " The Transportation Energy and Carbon Footprints of the 100 Largest U.S. Metropolitan Areas" (Southworth, Sonnenberg, & Brown, 2008). These estimates were achieved by first using Federal Highway Administration data to establish daily averages for vehicle-miles traveled for each county included in the metropolitan statistical areas involved. That data were then combined with data from the Oak Ridge National Laboratory's Transportation Energy Data Book to develop average fuel consumption values for cars. National-level data on fuel mixes used by cars across the country were included to ensure that the emissions reflected the ratios of gasoline, ethanol blends, and diesel in the national fuel mix. This measurement is not one of the components of emissions from household energy use, but is a component of an aggregate per-capita vehicle emissions variable that the authors generate.

Several variables were taken from the Census Bureau's 2007 State and Metropolitan Area Data Book. This source supplied the number of housing units in 2000, the housing density in 2000, the home ownership rate in 2004, and the percentage of housing units in buildings of two or more units (multi-unit housing, for short) in 2004. It also contains the data describing the number of acres converted from rural use per new house built from 1980 to 2000, as well as per-capita income values for 2000 and 2005. The 2000 variables were taken from the decennial census in 2000, and the 2004 data were developed through the Census Bureau's established methodology for population and housing estimation in non-census years. For those years, the Census Bureau uses the decennial census as a baseline, and uses responses from surveys of county government data to estimate the number of new houses constructed, the number of new mobile home placements, and the number of housing units lost. The Census Bureau relies on counties to submit these data, and imputes values where full data are not submitted. This work is done by the Manufacturing and Construction Division4.

Housing data from the extended model for the year 2005 came from the Census Bureau's American Community Survey (ACS). This includes the variables describing

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[4] the full methodology is available at the Census Bureau's website: http://www.census.gov/popest/topics/methodology/2007-hu-meth.html.

housing type (RVs/vans, detached houses, duplexes, and the rest), as well as the variable describing the median number of rooms of the homes in each MSA. The ACS collects data continually through an ongoing mail survey process. The survey methodology is similar to Don Dillman's(1978) widely-adopted method for mail surveys, and consists of a pre-notification letter, a survey questionnaire, a reminder card, and a second questionnaire for non-respondents. The ACS goes beyond Dillman's approach in its efforts to minimize non-response and incomplete response problems, first through telephone interviewing attempts to households that fail to respond to the mail questionnaire, and finally through direct site visits by field representatives to a third of all non-responding households. However, for the year 2000, the ACS only collected observations for housing type and number of rooms per MSA from a few specific test sites. Consequently, for a sufficiently large subset of the MSAs in the year 2000 lacked these data. Thus, this study only includes these available variables in the 2005. The Census Bureau publishes the standard errors for all of the values utilized in this analysis, and while they are small, they are in some cases very large compared to the measured quantity of housing types. In many of the smaller metro areas, infrequent housing types had larger reported standard errors than the actual number of households. Nevertheless, this occurred almost entirely with the category counting boats, RVs and vans, a category of housing which is not central to the question of how differences in emissions from household energy use correspond with variations in established housing stock. By contrast, the standard errors for other categories usually stayed below one percent of the measured number of households of any given type.

For energy prices, this study relied on the Energy Information Administration's tables of historical retail energy prices for states, listed by year. These prices are measured with all taxes included, thus representing the actual out-of-pocket gross price the consumer faces. As with weather data, where MSAs covered more than one state, the prices of the state containing the majority of the population were applied. No MSA was evenly split over two states; those with counties in more than one state were always predominantly in one state. Further, energy prices rarely varied significantly between adjacent states.

Data for per-capita income by MSA are provided for every year back to 1969, through the Regional Economic Information System maintained by the Bureau of Economic Analysis. It is derived from Census Bureau data5.

Some variables are created in the regression models constructed for this study. The first is a weighted land-use conversion rate. The model hypothesizes that a history of high levels of sprawl will result in a housing stock that is more consumptive of energy, even after controlling for the proportions of different housing types. The variable describing land-use conversion rates indicates how much rural land was converted for each new home, but does not indicate what proportion of the housing stock is characterized by that sprawl rate. As a consequence, a city that grew very rapidly during the 1980s and 1990s would be indistinguishable from a city that grew only slowly during that time, and if the two had the same per-house sprawl rate, this expression of sprawl

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[5] The data can be found at: http://www.bea.gov/iTable/iTable.cfm?ReqID=70&step=1&isuri=1&acrdn=4.

would treat them as equal. In actuality, the fast-growing city would have much more of its housing stock represented by that period than the slow-growing city would. To rectify this problem, this study used data from the American Community Survey to establish the number of housing units built during the period from 1980 to 2000. Then that value was divided by the measured number of total housing units in 2005, to establish a percentage of the housing stock to which the land-use conversion variable applied. This study created the weighted land-use conversion rate variable by multiplying the percentage of housing built during that time by the land-use conversion rate.

A similar problem presents itself in the case of the variable expressing the percentage of rental units for which landlords paid utility bills. In this case, the percentage of housing to which this variable applies was not reflected in the variable. As a consequence, cities with little rental housing and cities having a great deal of rental housing risked being treated equally. This study use data from the American Community Survey on the percentage of housing occupied by renters and multiplied the proportion of utilities-paid apartments by the proportion of rental properties overall. This weighted utilities-paid variable was included, rather than the straight utilities-paid variable, in the model.

One positive aspect of these sources of data is that the housing data, while not measured at the household level, avoid two of Randolph's (2008) critiques of Ewing and Rong (2008): using housing data with small sample sizes and using data sets with very different sampling frames. Ewing and Rong used data from the EIA's 2005 Residential Energy Consumption Survey, which sought to describe the entire US housing stock through a sample of only 4,381 households.6 The American Community Survey, by contrast, surveyed approximately three million households, or nearly three percent of all households, that year. Avoiding the RECS, with its significantly non-random method of carefully selecting a small sample of households to represent a sought-after composition, and using the ACS and Census data instead, is also beneficial from a sampling-frame perspective: the data for housing stock and for carbon emissions of a given MSA are assembled by aggregating sample data from each county within that MSA. While the data collection at the county level is not the same, this similarity at least ensures that the estimates for emissions and the estimates of housing stock characteristics are measuring the same populations in similar ways.

Weather data were taken from the National Climatic Data Center (NCDC) at the website of the National Oceanic and Atmospheric Administration[7]. Because metropolitan areas often cover many counties and much more geographic territory than cities do, this study elected to use data at the climate division level, rather than data from any individual weather station within the metro area. (Divisions are subparts of states, and there are anywhere between one and ten divisions per state.) For example, the Riverside-San Bernardino-Ontario MSA in southern California includes all of San Bernardino County, and thus extends from near the west coast all the way to the Nevada and Arizona borders. To use data from Riverside alone would misrepresent the average

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[6] See the website for the methodological explanation: http://www.eia.doe.gov/consumption/residential/

[7] http://www.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html

temperature for the larger MSA. The climatic division for that area provides a more appropriate, and consistently available, estimate, obtained by averaging temperature readings taken three times per day at dozens of monitoring stations throughout each division.8 Divisions lie strictly within state boundaries, while MSAs often cross state boundaries, and in some cases include counties in three states. In cases where an MSA extended across a state line, and thus into a second division, a single climatic division was selected and applied its averages to that MSA. This study did so by taking into account which division had the greater share of population. Of eighteen MSAs with counties in more than one state, all had a clear preponderance of total population in one division. For example, the MSA surrounding Louisville, Kentucky lies mainly in Kentucky but also includes a county in Indiana. Its population is mainly in Kentucky, and so I used data from the climatic division in northern Kentucky covering Louisville itself, and disregarded the division in southern Indiana. Table 3 contains data sources and variables used for this analysis.

Additionally, because a number of variables are not available for the Honolulu MSA in forms that are consistent with their measurement in other MSAs, this study exclude Honolulu from these models, resulting in only ninety-nine of the top 100 MSAs being considered in the models.

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[8] A full methodology is available at NOAA's website: http://www.ncdc.noaa.gov/ CDO/DIV_DESC.txt.

Table 3 Data Sources

Data Source	***Variables***
Census Bureau's State and Metropolitan Area Data Book	the number of housing units in 2000, the housing density in 2000, the home ownership rate in 2004, the percentage of housing units in buildings of two or more units (multi-unit housing, for short) in 2004. the number of acres converted from rural use per new house built from 1980 to 2000, per-capita income values for 2000 and 2005
Census Bureau's American Community Survey (ACS)	housing type (RVs/vans, detached houses, duplexes, and the rest), the median number of rooms
National Climatic Data Center (the NCDC)	data at the climatic-division level ; HDD, CDD
Energy Information Administration	retail energy prices for states
The Transportation Energy and Carbon Footprints of the 100 Largest U.S. Metropolitan Areas	per-capita vehicle emissions (vehicle related energy use in each MSA)
The Residential Energy and Carbon Footprints of the 100 Largest U.S. Metropolitan Areas 2008(Brown & Logan, 2008)	per-capita annual energy use from residential electricity and fuel consumption

CHAPTER IV

ANALYSIS AND RESULTS

4.1 Analysis

In order to measure the relative impacts on residential energy consumption of different characteristics of urban housing, this study focuses on two different regression models. Both models attempt to measure the correlation of several characteristics of housing stock and indicators of urban form with variations in household energy use.

The hypothesis underlying this analysis is that communities with characteristics of greater density will show significantly lower per-capita energy consumption from their residents than will communities with characteristics of sprawl. This analysis seeks to measure whether these characteristics do in fact correspond to residential energy consumption. If they do show an influence on energy consumption, specifically annual per capita home energy use, the second question of interest is whether or not they closely correspond to the scales of the effects.

Using ordinary least squares (OLS) regression, data from the 100 largest metropolitan statistical areas in the United States is analyzed. Ordinary least squares regression is a widely using method for estimating the relationships of explanatory variables. The formula in this analysis maps out a straight line graph with slope and Y-intercept. It is very useful to calculate unknown parameters in a linear regression model. (Agresti, 1997)

The model is also run with the weighted land-use conversion rate in quadratic form, to show how relationships between the energy consumption and the independent variables differ between 2000 and 2005. Expressing this variable in quadratic form may improve the model for two reasons. First, to the extent greater land conversion allows for more energy-consumptive housing stock (via larger square footage or larger footprints), that effect is likely to diminish after a certain point, when housing becomes so widely spaced that limited land is no longer a limiting factor in design. Also, the variable may show a non-linear which is positive but diminishing relationship with energy use because more housing stock can be added in a dense fashion and still increase the value of the variable. In fact, the regression results show that the strongest model for 2000 contains this variable in linear form, while the strongest model for 2005 contains the variable in quadratic form, and both versions of each year's model are included to show the difference.

The 2005 regression model is also run with the multi-unit variables merged into two categories, *TwotoNinepct05* and *TenPluspct05*. A third model is run with all the multi-unit variables, but replaces the T*wentyPlusPct05* variable with the *DetachedPct05* variable, in order to compare the results with alternate reference categories.

4.2 Summary Statistics

Tables 4 and 5 report the mean, the maximum value, and the minimum value for each variable utilized in this regression analysis. Table 4 reports this information for 2005, while table 5 reports this information in the year 2000. The second column in each of the two tables reports these values for the overall sample of 100 MSAs, while the middle column reports the same information for the 50 lowest per-capita energy consumers; the last column in each table reports parallel information for the 50 highest per-capita energy consumers.

Table 4 Summary Statistics for Regression Variables in 2005

	100MSAs		*low 50*		*high 50*	
	mean	max&min	mean	max&min	mean	max&min
per-capita housing	60.491	36.511	57.043	36.511	75.362	89.409
Energy consumption	12.993	89.409	10.351	67.132	5.687	67.288
Per Capita Auto	1.090	1.283	1.060	1.484	1.121	1.402
emission	0.182	0.064	0.206	0.664	0.150	0.767
Per Capita Income	35,554.27	68,840	36,085.42	68,840	35,023.12	49,442
	6,446.74	19,926	8,274.66	19,926	3,863.08	27,927
percent detached housing	61.758	75.909	59.906	72.628	63.574	75.909
	7.547	36.712	7.564	36.712	6.956	44.098
percent duplex housing	4.15	19.93	4.161	19.93	4.14	12.796
	3.341	1.042	3.806	1.042	2.853	1.156
percent 3-4 unit housing	4.846	14.575	5.016	10.813	4.679	14.575
	2.156	1.993	1.887	2.736	2.398	1.993
percent 5-9 unit housing	5.503	10.831	5.668	10.831	5.342	7.927
	1.413	1.925	1.34	3.23	1.477	1.925
percent10-19 unit housing	4.913	10.927	4.851	10.927	4.973	10.199
	1.921	1.114	1.902	1.226	1.956	1.114
percent 20+ unit housing	7.314	26.998	8.352	26.998	6.297	14.676
	4.183	2.084	4.963	2.991	2.953	2.084
weighted land-use	42.04	127.17	28.3	124.22	55.78	127.17
conversion rate	34.53	0.72	28.62	0.72	34.71	6.87
residential energy price	9.99	20.7	11.06	20.7	8.93	13.64
	2.66	6.29	2.95	6.29	1.81	6.57
median rooms	5.49	6	5.37	6	5.6	6
	0.3	4.7	0.31	4.7	0.24	5.2
housing growth 00-04	6.90%	22.10%	7.50%	22.10%	6.30%	16.50%
	4.30%	1.20%	4.90%	1.30%	3.60%	1.20%
2004 housing density	220.4	1,076.30	259.6	1,076.30	181.1	506
	185.4	17.8	230.8	17.8	114.2	38.6

Table 5 Summary Statistics for Regression Variables in 2000

	100 total		*low 50*		*high 50*	
	mean	max&min	mean	max&min	mean	max&min
per-capita housing	62.612	89.409	55.121	65.414	75.681	89.409
Energy use	13.001	30.317	12.003	30.317	5.953	66.242
Per Capita Income	30,632.09	58,997	31,135.72	58,997	30,128.46	40,667
	5,811.26	18,572	7,549.26	18,572	3,274.40	23,916
ownership rate 2000	-	1	-	1	-	1
	-	0	-	0	-	1
residential energy price	8.77	16.41	9.462	16.41	8.08	12.49
	2.17	5.13	2.54	5.13	1.45	5.47
adjoin rate 2000	33.00%	56.70%	35.10%	56.70%	30.80%	43.40%
	6.20%	20.80%	6.70%	24.20%	4.70%	20.80%
housing density 2000	208.26	1054.3	246.28	1054.3	170.22	492.9
	181.71	15.4	226.36	15.4	111.9	35.9

From these tables, we can see that overall per-capita energy use for the 100 MSAs in this sample averaged 60.491MBtu per person in 2005, falling from 62.612MBtu per person in 2000. Sixty-four of the 100 MSAs saw their per capita home energy use drop, with the rest experiencing an increase in the per-person average.

Table 6 and 7 compare the lowest household energy consumed MSAs and the 10 highest household energy consumed MSAs. Table 6 reports this information for 2000, while table 7 reports this information in the year 2005. The Washington, DC area was the highest energy consumer on a per-person basis in both years and its per-capita consumptions grew, rather than shrank, from 71.867MBtu to 85.783MBtu.

Table 6 Energy Consumptions from Household Energy Use 2000

	residential per capita energy use (MBTU/person)	*residential energy price (cents/kWh)*	*multi-unit rate*	*housing units per square mile*	*weighted land conversion rate 1980-2000*
Lowest energy users					
Los Angeles, CA	36.511	10.89	42.2	874.3	4.06
Seattle, WA	61.217	5.13	37.2	213	8.96
Portland, OR	60.488	5.88	34	118.3	27.89
San Diego, CA	38.294	10.89	39.6	247.7	13.92
Boise City, ID	71.562	5.39	25.2	15.4	72.88
Riverside, CA	40.791	10.89	29	43.5	27.13
Oxnard, CA	40.856	10.89	25.4	136.4	8.02
Bakersfield, CA	42.578	10.89	28.9	28.4	35.72
Fresno, CA	44.081	10.89	31.5	45.4	53.31
San Francisco, CA	45.812	10.89	41	649.7	0.98
Highest energy users					
Kansas City, MO	80.387	7.04	25.7	97.7	57.56
Toledo, OH	81.603	8.61	29.9	176.3	54.76
Oklahoma, OK	81.806	7.03	27.2	85.6	50.46
Tucson, AZ	82.386	8.44	38.5	39.9	1.79
Tulsa, OK	82.685	7.03	28.4	58.3	100.99
Louisville, KY	83.35	5.47	28.5	119	103.21
Youngstown, OH	83.609	8.61	22.9	150.7	127.99
Indianapolis, IN	83.856	6.87	28.2	166.9	41.28
Lexington, KY	84.35	5.47	33.6	118.5	79.85
Washington, DC-VA-MD	88.851	8.03	33.9	335.9	24.8

Table 7 Energy Consumptions from Household Energy Use 2005

	residential per capita energy use (MBTU/person)	*residential energy price (cents/kWh)*	*multi-unit rate*	*housing units per square mile*	*weighted land conversion rate 1980-2000*
Lowest energy users					
Bakersfiled,CA	30.684	12.51	33.92	30.4	32.17
Seattle, WA	37.086	6.54	34.79	227.0	8.08
San Diego, CA	37.580	12.51	39.05	261.7	12.78
Riverside, CA	40.492	12.51	29.14	47.9	23.85
San Jose, CA	41.085	12.51	37.79	230.7	4.83
Fresno, CA	42.152	12.51	39.74	48.0	49.63
San Francisco, CA	42.433	12.51	39.50	669.1	0.94
Los Angeles, CA	43.063	12.51	45.68	892.6	3.91
Portland, OR-WA	43.215	7.25	34.29	126.3	24.97
Oxnard, CA	43.967	12.51	29.46	143.2	7.46
Highest energy users					
Baltimore, MD	80.591	8.46	29.02	414.9	14.41
Oklahoma, OK	82.435	7.95	32.05	90.2	46.33
Tulsa, OK	82.436	7.95	28.64	61.0	93.09
Dayton, OH	83.41	8.51	29.06	219.4	22.16
St. Louis, MO-IL	85.547	7.08	24.36	136.8	73.10
Louisville, KY	85.783	6.57	26.89	126.8	93.64
Indianapolis, IN	86.526	7.50	27.27	183.5	35.90
Cincinnati, OH-KY-IN	87.735	8.51	27.93	200.1	46.68
Lexington, KY	87.843	6.57	34.22	128.5	70.56
Washington, DC-VA-MD	88.315	9.10	31.32	361.4	22.46

An examination of the MSAs in the data set strongly suggests that individual MSAs, even nearby MSAs, face differing factors influencing their energy consumptions. For example, Los Angeles, which held the lowest-per-capita energy use mark at 0.376 in 2000, rose about 4% to 0.391 by 2005. By contrast, Bakersfield, CA, which is located just 100 miles away, took over the lowest spot in 2005 when it showed a dramatic drop just five years later. Bakersfield's experience constitutes a 19% drop in just five years, which is dramatic and raises interest in finding out which explanatory factors also changed significantly over that time period. Its per capita energy use also dropped by about 15%, so – based on initial evidence - any change to a cleaner fuel mix seems to only be responsible for a minority of the change. In case of Texas, Austin held the lower per capita energy consumptions mark at 46.902Btu in 2000, rose to 65.352Btu by 2005. By contrast, Dallas-fort-worth consumed as twice as much compared to Austin in 2000 but slightly decreased five years later. Other MSAs in the data set also had large decreases from 2000 to 2005, approaching 20 percent reductions, while a few had large increases nearing 20 percent. Cincinnati's housing-based emissions jumped a full 20%, while its energy use only jumped about 17%. In fact, at both extremes, emissions changed more dramatically than energy use. This is an early indicator that fuel mix, in addition to being a control variable for the purposes of this model, can manifest changes quickly enough to also be viewed as a potentially relevant policy variable.

Residential energy price shows an interesting result in the summary statistics. The average energy price for the lowest 50 energy using MSAs is a full 20% higher than for the highest 50 energy using MSAs in both 2000 and 2005. This suggests that price sensitivity may be a variable to watch in the final analysis.

Per capita income over the entire sample grew dramatically –a total of over 16% ($30,632 to $35,554) from 2000 and 2005. Interestingly, the half of the sample with lower emissions from households held a consistent advantage in per-capita income of about $1,000 in both years measured (2000 and 2005). This is despite wide variations from city to city – rates of increase range from 15% to nearly 50% over that time.

The population-density data reported in Tables are immediately interesting. Population density for the 50 lower energy using MSAs in the sample was about 57% higher in 2000 and 2005 than the 50 higher MSAs. This number barely varied, staying between 56% and 58%, despite the fact that overall, the group grew very rapidly, and that cities varied widely in the changes in density they experienced.

Based on the summary statistics, housing-related variables also appear to be correlated with per-capita energy consumptions. The 50 lower energy consumers had far higher housing density overall (about 35% in both 2000 and 2005), and higher rates of multi-unit housing (about 16%) than the high energy consumers.

This study hypothesized detached housing to be a driver of increased energy consumption. Looking at the 2005 extended model, detached housing does indeed represent, on average, four percent more of the housing stock for the 50 highest energy users than it does for the 50 lowest energy users. On the other hand, it is expected that highly-dense forms of multi-unit housing (five to nine units, ten to nineteen units, and twenty or more units) to correspond with lower emissions. The summary statistics are in line with my hypothesis for two of those three categories, but the ten-to-nineteen-unit housing appears to represent more of the housing stock in the 50 highest energy using MSAs than it does in the 50 lowest MSAs.

The weighted land-use conversion rate is dramatically lower for the lowest 50 MSAs, indicating the possibility of a strong relationship between a history of sprawl and present-day energy consumption. The average value for the median rooms per household is lower for the lowest 50 MSAs, which is entirely in line with the literature on this subject. Smaller spaces are expected to require less energy to heat and cool.

4.3 Regression Results

The results are reported in two tables. Table 8 displays the results using variables available for both 2000 and 2005. Table 9 compares three alternate specifications of the extended model for 2005. It is also worth noting that in Table 8, two alternative specifications of the model are shown for each year; the first model specification reported uses the weighted rate of land conversion in linear form, while the second specification reported uses it in quadratic form. All references to the results of Table 6, unless otherwise specified, refer to the first model from 2000 and to the second model from 2005; these two were each stronger models than their respective alternatives.

In the table for the extended 2005 model, three different specifications are shown. In the first column, all of the housing categories are compared against the reference category of single-family detached housing. In the second column, but the multi-family housing variables have been aggregated into categories of two to nine units and ten or more units. In the third column, the category of housing in buildings of 20 units or more is held out as the reference category, and all the other categories are included.

Table 8 Regression Results from Comparison Model (2000, 2005)

	2000		*2005*	
Energy Price	-0.06493 ***	-0.06472 ***	-0.05687 ***	-0.05786 ***
	0.01173	0.01161	-0.01023	0.00987
% of homes in multi-unit building	-0.00484	-0.00357	0.00186	0.0041
	0.00401	0.00403	-0.0038	0.00375
Housing Density	-0.00013	-0.00008	-0.00028 **	-0.00018
	0.00012	0.00012	-0.00013	0.00013
Land-Use Change Rate	0.00211 ***	0.00491 ***	0.00104	0.00633 ***
	-0.00056	-0.00174	-0.00062	0.00203
Weighted Land-Use Change Rate (squared)	--	-0.00002 *	--	-0.00004 ***
		0.00001		0.00002
Per-Capita Income	1.74 x10-	2.73 x 10-6	6.06 x 10-6 **	7.40 x 10-6 **
	3.16 x 10-6	3.18 x 10-6	3.04 x 10-6	2.97 x 10-6
% of homes occupied by Owners	-0.00625	-0.00457	-0.00827	-0.00555
	0.00596	0.00597	0.00575	0.00563
Heating Degree-days (logged)	-0.02619	-0.04135	-0.00252	-0.02731
	0.04167	0.04217	0.04806	0.04721
Cooling Degree-Days (logged)	-0.04985	-0.05319	-0.01985	-0.02849
	0.03814	0.03777	0.04602	0.04448
Northeast Regional Dummy	0.32525 ***	0.29864 ***	0.35611 ***	0.30966 ***
	0.07599	0.07678	-0.08943	0.08787
Midwest Regional Dummy	0.19605 **	0.16937 **	0.15447 *	0.10972
	0.07519	0.07601	0.08859	0.08696
Southeast Regional	0.04643	0.04666	0.10641	0.06185
	0.0743	0.07766	0.08247	0.08116
Southwest Regional	0.01317	0.05674	0.01752	0.00601
	0.07838	0.08121	-0.08546	0.08249
Constant	3.09360 ***	3.02072 ***	2.63080 ***	2.51123 ***
	0.77979	0.77247	0.92962	0.89723
Observations Adjusted R2 F-test	99	99	99	99
	0.7986	0.803	0.8065	0.8201
	30.9	29.53	32.41	32.92

Dependent variable is energy use in Btus

˙ (0.05opr0.1)

* (0.01opr0.05)

** (0.001opr0.01)

*** (pr0.001)

Table 9 Regression Results from Extended Model (2005)

	version 1	***version 2***	***version 3***	***version 4***
Price of Residential Energy	-0.06405 ***	-0.07255 ***	-0.06405 ***	-0.06872 ***
	0.0113	0.01177	0.0113	0.01158
Percent of Rental Units	0.00036 **	0.00030 *	0.00036 **	0.00027 *
	0.00015	0.00016	0.00015	0.00016
Percentage of Mobile Homes	-0.01418 **	-0.01492 *	0.00813	-0.01575 **
	0.00685	0.00752	0.00847	0.00756
Percentage of Boats, Vans, RVs	-0.03769	0.01403	-0.01539	0.01997
	0.30008	0.32856	0.30039	0.33119
Percentage of Detached Housing	----	----	0.02231 ***	0.005
			0.00627	0.00499
Percentage of Row Housing	-0.01113 **	-0.01045 **	0.01118	-0.01285 ***
	0.00458	0.00497	0.00728	0.00475
Percentage of Duplexes	0.00192		0.02423 **	
	0.00701		0.00946	
Percentage of 3-4 unit housing	0.00332		0.01899 *	
	0.01045		0.0109	
Percentage of 5-9 unit housing	0.0087		0.03100 **	
	0.01359		0.01272	
Percentage of 10-19 unit housing	0.02591 ***		0.04821 ***	
	0.01066		0.01352	
Percentage of 20+ unit housing	-0.02231 ***			
	0.00627			
Percentage of 2-9 unit housing	----	0.00166		
		0.00557		
Percentage of 10+ unit housing	----	-0.00734		
		0.00505		
Median Rooms	-0.03949	0.38748	-0.03949	0.03149
	0.09037	0.09639	0.09037	0.09705
Weighted Land-Use Change Rate 1980-2000	0.00723 ***	0.00620 ***	0.00723 ***	0.00605 ***
	0.00192	0.00203	0.00192	0.00204
Land-Use Change Rate, squared	-0.00005 ***	-0.00004 ***	-0.00005 ***	-0.00004 ***
	0.00001	0.00001	0.00001	0.00001

Dependent variable is energy use in Btus
˙ (0.05opr0.1)
* (0.01opr0.05)
** (0.001opr0.01)
*** (pr0.001)

Table 9 Continued

	version 1	***version 2***	***version 3***	***version 4***
Per-Capita Automobile Emissions	0.01755	0.09006	0.01755	0.08239
	0.09051	0.09776	0.09051	0.09842
Housing Density per Square Mile 2004	0.00003	0.00008	0.00003	0.00009
	0.00013	0.00013	0.00013	0.00014
Per-Capita Income	8.91 x 10-6 **	9.71 X 10-6 **	8.91 x 10-6 **	8.24 x 10-6 **
Percent of Owner-Occupied Homes	-0.00168	-0.00678	-0.00168	-0.00655
	0.00618	0.00629	0.00618	0.00634
Heating Degree-days (logged)	-0.12733 **	-0.11474 **	-0.12733 **	-0.09089 *
	0.05069	0.05501	0.05069	0.05311
Cooling Degree-Days(logged)	-0.03108	-0.00675	-0.03107	0.00007
	0.04108	0.04479	0.04108	0.04492
Northeast	0.31403 ***	0.32380 ***	0.31403 ***	0.37045 ***
	0.09787	0.10692	0.09787	0.10315
Midwest	0.08211	0.08697	0.08211	0.09175
	0.07833	0.08584	0.07833	0.08647
Southeast	-0.02774	0.01067	-0.02774	0.0317
	0.08455	0.0893	0.08455	0.08891
Southwest	-0.08501	-0.03744	-0.08501	-0.05031
	0.07996	0.08529	0.07996	0.08555
constant	3.33947 ***	3.07365 ***	1.10887	2.92509
	0.94549	0.98184	0.8533	0.98475
Observations Adjusted R2 F test	99	99	99	99
	0.8666	0.8381	0.8666	0.8355
	34.85	25.16	27.53	25.88

Dependent variable is energy use in Btus
˙ (0.05opr0.1)
* (0.01opr0.05)
** (0.001opr0.01)
*** (pr0.001)

CHAPTER V

DISCUSSION AND CONCLUSIONS

5.1 Discussion

5.1.1 Residential Energy Consumption

Annual per-capita residential energy consumption ranged in this sample from around 30.317 MBtu to a value over three times as high, nearing 88.851MBtu per person. The mean amount of per-capita residential energy consumption in both 2000 and 2005 was almost 61MBtu per person, with a standard deviation at about13.05. The numbers from 2005 were slightly higher. Figure 6 shows the distribution of energy consumption in 2005 graphically.

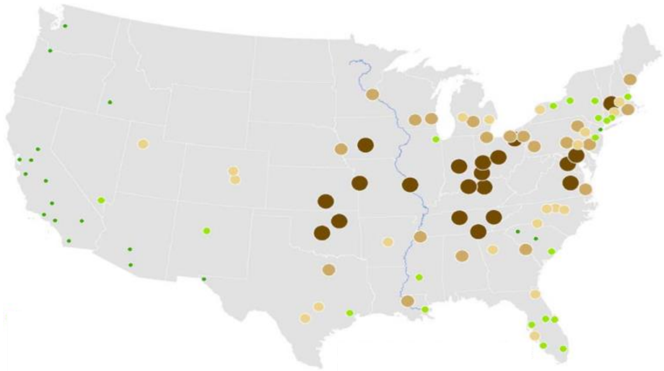

Figure 6 Distribution of Energy Consumption in 2005

5.1.2 Housing Characteristic Variables

In the comparative model, this study used only a single variable to describe variation in housing form. A variable expressing the percentage of housing that was in buildings with two or more units was used. More refined data was available for 2005, but not for 2000, and so this study limited the model to a simple approach in order to get a valid comparison.

However, in such a simple form, the model showed no significant relationship between the percentage of multi-unit housing and residential energy consumption in either 2000 or 2005. The extended model, by contrast, divides housing into a range including nine categories, from RVs and vans on one end to buildings with more than 20 units on the other. In the first two variations of the extended model, detached single family housing was excluded from the model, and used that category as a reference against which to compare other categories. The difference between the two is simply that in Version 1, this model compares single-family detached homes against different categories of housing. It includes everything from RVs and vans to high-rise apartment buildings with 20 or more units. While in Version 2, the multi-family housing categories were grouped into larger aggregations that more closely reflect the literature up to this point. Specifically, this model aggregated duplexes, 3-4 unit buildings, and 5-9 unit buildings into one category. This study also aggregated the ten-to-nineteen-unit buildings together with the buildings with more than 20 units, creating a larger “10 or more” category. In Version 3, housing in buildings containing more than 20 units was established as the reference category, and compared all other subcategories against that category, rather than against detached single-family housing.

In Version 4, all categories describing housing in buildings containing two or more units are aggregated, in order to compare multi-unit housing against detached single-family housing in a manner similar to the previous studies. Mobile homes showed a consistently statistically significant effect, when compared against detached single-family homes. Replacing one percent of detached homes with mobile homes, while holding other forms constant, correlates with a decrease in household energy consumption. As a housing form, however, mobile homes are abnormally small in terms of square footage per housing unit, and their occupants are almost certainly clustered around a low average income (which is also strongly correlated with energy consumption reductions), and so it is most likely that a planning preference for mobile homes is not a practical approach to energy conservation.

Along the same lines, boats, vans and RVs showed no significant effect when compared against detached single-family housing, and are outside the realistic scope of housing policy anyway. More importantly to this analysis, Attached single-family housing, or row housing, showed a consistently significant effect. This was true in all three versions that compared the two forms (versions 1, 2 and 4 in Table9). When compared against high-rise housing in Model 3, an increase in row housing did not have a significant effect.

Duplexes showed no significant energy-reducing impact when compared against detached single-family homes. Both by themselves and as part of a large subset of homes in buildings with between two and nine units, changes in the incidence of duplex housing showed no correlation with an upward or downward trend. When compared against high-rise housing, however, they showed a large upward impact on energy uses – twice the size that the model predicts for row housing. Shifting one percent of housing away from high rises and into duplexes corresponds to an increase in per-capita energy use of 1.18 MBtu per year.

This leads to a useful observation about housing type from a planning perspective: given that row housing shows significantly (both statistically and in a practical sense) lower energy use than duplex housing, local planners seeking to control energy use and related emissions now have evidence that suggests row housing to be a superior option to duplexes for neighborhoods in which high-rise or true multi-unit housing is a governmentally unpopular option.

Low-Rise Multi-Unit Housing does not produce strong or consistent results in this analysis. Neither the category of three-to-four unit housing, nor the category of five-to nine unit housing, shows a statistically significant relationship with energy consumptions when compared against single-family detached housing, when compared against detached single-family housing. Taken together with duplexes to make one larger category in Version 2, they again show no statistically significant relationship – the standard error is larger than the measured effect.

When compared against high-rise housing with 20 units or more, however, they produce somewhat significant results. Three-to-four unit housing shows a large and weakly significant effect on energy consumption – the model suggests that converting one percent of all homes from high-rise housing to three-to-four unit housing would correlate with an increase of 0.019 in per-capita energy use. Five-to-nine unit housing shows an even larger difference, which is statistically significant at $p < 0.05$. The difference for both categories when compared against 20+ units housing is reinforced in Version 1: 20+ units housing shows a strong correlation with energy savings when compared against detached single family homes, while the other two show no statistically significant effect. The difference between the 20+ unit coefficient and the effects for the other categories is about the same as the difference shown in Version 3. High-Rise Multi-Unit Housing shows interesting and unexpected results.

In short, while 20 and more unit housing shows a significant and strong correlation with lower energy consumptions, 10-19 unit housing does not. When compared against detached single-family housing in Version 1, 20+ unit housing dutifully produces a strong result – a shift of one percent of housing stock from detached to 20+ unit housing result in 0.022 Btu reduction.

By contrast, variation in the amount of housing in buildings of 10 to 19 units shows a small positive relationship with per-capita emissions, although it is by no means statistically significant. I raise this meaningless result only because it is reinforced in Version 3, where 10-19-unit housing shows a much stronger positive relationship with emissions when compared against 20 and more unit housing than even the single-family detached housing. The model suggests strongly that shifting 20 and more unit housing to 10-19 unit housing would drive emissions upward even more rapidly than shifting the same amount of 20 and more unit housing to detached single family homes.

It is reinforced in its strangeness by the fact that the 10-19 categories are a clear outlier in Version 3. The intuitive notion that joined housing produces efficiencies through smaller space and shared walls is basically confirmed by all the other variables, but not by that one. When compared to 20+ unit housing, 5-9 unit housing corresponds with higher emissions, 3-4 unit housing corresponds with emissions that are even higher, and duplexes and detached homes correspond with emissions that are higher still. This suggests a trend: as the number of units increases, energy consumption per person goes down. The 10-19 unit result goes entirely against that trend, appearing to produce energy-consumption levels around those of detached housing.

Model 2 bumps the 10-19 unit and 20+ unit categories together into one category containing all housing in buildings with more than 10 units. The resulting "10+" variable has no statistically significant emissions-reduction effect when compared against detached single-family housing. In my view, this only serves to obfuscate the unexpected difference between the 10-19 unit and over-20-unit sub-parts of the larger category.

Median number of rooms per housing unit showed no significant correlation with home energy use. While it is expected that this variable might correlate positively with per-capita energy use, the inability of this model to capture either occupancy rates of housing units leaves unmeasured an important factor that could easily disprove the impact of variation in housing size, especially when considering per capita energy consumption.

5.1.3 Urban Form Variables

The weighted land-use change rate variable expresses a measurement of how much rural land was converted to developed land for each new house built during the time period 1980 to 2000, multiplied by the percentage of total housing stock built during that period. The percentage was calculated separately for 2000 and for 2005, to take into account housing stock built after 2000. This variable represents the number of rural acres converted from 1980 to 2000. It is divided by the total number of housing units in the year. It effectively represents the impact of a period of housing development on the overall energy consumption of the entire housing stock. The coefficient expresses the relationship between an additional hundred rural acres converted and the per-capita household energy use. The variable strengthened the model most, and showed the most significant effect, in quadratic form, although the coefficient for the squared term was very small compared to the coefficient for the linear term.

The results show that communities that have a large amount of their housing built in a highly land-consumptive manner see higher per-capita residential energy use. The negative sign on the squared term indicates that this impact lessened slightly for those MSAs scoring highest in this sprawl category. Some MSAs, such as the New York City area, converted only a small amount of land during the 80s and 90s per housing unit. Others, like Little Rock or Chattanooga, converted huge amounts of rural land for development during those two decades. The coefficients for the comparative model (ranging between 0.0049 and 0.0063) strictly state that for each additional 0.1 acres converted per housing unit, per capita household energy use went up by a little more than 0.05 Btus. Because the variable is expressed in quadratic form, and the squared term in negative, that effect recedes slightly as the variable gets larger. The effect is slightly larger in the extended model, where the coefficient for this variable ranges from 0.0062 to 0.0072. This model observes an effect of between 0.06 and 0.07 Btus for each tenth of an acre converted during the 1980s and 1990s.

The correlation between per-capita carbon footprint from highway auto use and the per-capita carbon footprint from household energy consumption was only included in the extended model because data was available only for 2005. There was never statistically significant in any variation of that model.

Finally, housing density per square mile actually showed no significant relationship to per-capita household energy use. This is likely due to the fact that the models already controlled for the percentages of the housing forms that would drive density, as well as controlling for median number of rooms. The likely mechanism through which density would affect emissions is by driving changes in housing form or by reducing size. In the absence of variables describing how density is distributed throughout a metro area, this variable helps us observe differences that a simple average-density value cannot.

After all, the model controls for the overall housing density of each metro area, but this (or any) simple aggregate measure has been roundly criticized as insufficient to describe the multi-faceted nature of sprawl. Within communities of roughly similar overall housing density, however, some may be relatively evenly dense throughout, while others may have dense cores and very low-density surrounding areas. Some may have services, schools and employment centers concentrated in a few areas, while others may have them more evenly distributed. Ewing, Pendall and Chen (2002) provide a history of the development of approaches to modeling urban sprawl in social science research. In their work, they create a multi-faceted sprawl index based on 22 measurable components, grouped into categories concerning the incidence of mixed-use development, strength of downtowns, density, and the accessibility of the street network. That index was not generated for all of the MSAs in this study, and so it was not utilized. Brown and Logan (2008) also avoid a simple density variable, preferring to look at the degree of concentration of housing into core areas rather than a simple average.

5.1.4 Cost of Energy

The coefficient for the Energy Price variable was highly statistically significant, and indicates real price sensitivity on the part of energy consumption. The results ranged between -0.0057 and -0.0064 in the comparative model and between -0.0064 and - .0072 in the extended 2005 model. These indicate that for every cent that the kilowatt-hour price raised, household energy consumption fell by nearly a tenth of a ton per person per year. This is a large change, when we consider that most metro areas had average per capita footprints between 0.7 and 1.Btus per person per year.

This suggests that higher prices may significantly curb energy use and consequently carbon emissions. Much of the discussion of controlling individual energy consumption has been around improving consumers' control over their consumption by incorporating programmable thermostats and smart meters into the homes. Others have proposed schemes of real-time price adjustment with immediate information transmission, so that price can respond to load demand and consumers can adjust the timing of their consumption in ways that mitigates peak-demand problems. This analysis further supports the notion that using price to control demand is a strategy option that shows potential.

Significantly, the result also strongly suggests that a moderate, increase in energy pricing can achieve, in short order, emissions reductions similar in scale to dramatic investment in clean energy sources. Improving consumers' ability to control their consumption and cautiously using price as a tool to control residential energy consumptions are two very effective techniques for planners interested in tackling climate change. Particularly during the years in which new generation and transmission are debated, sited, approved, financed and built, pricing mechanisms offer a powerful way to jump-start the carbon emission-reduction effort.

5.1.5 Control Variables

The Percent of Housing that is Owner-Occupied variable had no statistically significant correlation with energy uses in either the comparative model or the 2005 extended model. Given the absence of variables better controlling for the differences between owned and rented housing, this is not a variable that should influence planning decisions by itself. This study includes it solely as a control variable, for that reason as well as it improved the overall strength of the models.

The coefficients for the weather variables are at variance with the literature (Berry, 2003; Eto, 1988; Pardo, Meneu, & Valor, 2002; Quayle & Diaz, 1980). This analysis finds no significant relationship between cooling degree-days (how much hot weather an MSA experiences) and an MSA's emissions from home energy use. By contrast, there is a significant relationship between energy uses and heating degree-days (how much cold weather an MSA experiences). But that correlation is negative, suggesting that areas with more extreme cold-weather patterns actually use less energy. This is contrary to both the expected effect and to the effect found by Ewing and Rong (2008), who found highly significant positive correlation between both heating and cooling degree-days and energy use.

Also, the research of the Energy Information Administration describes a highly significant level of importance to the effect of temperatures on energy consumption – in fact, they go so far as to say that encouraging growth in more temperate regions would do more to control energy use than controlling housing form (Energy Information Administration, 1999). However, their analysis did not divide housing stock as this analysis does, or as Ewing and Rong (2008) did. It also did not include regional dummy variables, which this analysis does, and which could reduce the observed correlation between weather and emissions. That being said, the coefficients for the weather variables remained statistically insignificant even when measured without the inclusion of regional dummy variables, so inclusion of those dummies did not mask a significant relationship.

One explanation of the differing results is that previous researches find a correlation between housing size and warmer weather, the inclusion of median number of rooms may have unconsciously removed much of the actual impact of weather. Another explanation may lie in Brown and Logan's assertion that colder weather (specifically, heating degree-days) were highly correlated with fuel mix. By controlling for fuel mix in these models, the analysis have accidentally controlled for much of the effect of weather. The primary value of weather is as a control variable, so that planning can isolate out the effects of factors that are more amenable to manipulation.

5.2 Limitations

There are a number of limitations of the analysis presented here that are worth observing. First, model used in this study does not include controls for occupancy rates of different types of housing units. Occupancy rates refer to the number of individuals living in an occupied housing unit, and not to the percentage of all housing that is occupied. There is some evidence to suggest that lower occupancy rates per unit correspond to higher per capita energy consumptions, and that emissions per housing unit level off as occupancy reaches four people. Holloway and Bunker (2006) cite a local-government survey of over 4,000 homes in the Sydney area, in which per-capita emissions from household energy use were found to be over twice as high for homes with one or two occupants as they were for homes with four or more occupants(Holloway & Bunker, 2006). It may be that occupancy levels per unit, unmeasured in these models, vary among single-family and multi-unit housing categories to a degree that they impact the magnitude, and even the significance, of the coefficients for housing types. Such a variance across categories may also be part of the cause of the strange results associated with multi-family housing categories when compared against the 20+ category in the extended 2005 model.

Second, the models contain no controls for the size of housing units. Such a control would be valuable, and would likely improve both the models' strength and the real-world applicability of their results. Ewing and Rong (2008) assert that expanding a housing unit from 1,000 square feet to 2,000 square feet corresponds to a 16% increase in its energy use. Guides from government agencies concerning energy costs attribute large increases in heating and cooling costs to greater housing size(Winfield, Gibson, Markvart, Gaudreau, & Taylor, 2010). The American Community Survey data from 2005 indicate that, among vacant housing units surveyed throughout the country, over 90% of units in single-unit structures had four or more rooms, while only about 55% of units in multi-unit structures had four or more rooms. By virtue of having been unmeasured in the models, the association of multi-unit housing with smaller size is likely to have influenced the magnitudes of the coefficients for the multi-unit housing variables. Controlling for housing size would also be helpful to the statistics concerning the rate of renter and owner occupancy. According to the American Community Survey data from that year, the median room size for rental units was 4.1 rooms in 2005 nationwide. While the median size for owner-occupied unit was 6.1 rooms – a dramatic difference. The consideration that owner occupancy likely corresponds to larger home size suggests that, left unmeasured, the models in this study underestimate any energy saving correlation that would be shown by owner occupancy percentages if housing size were effectively captured in the model.

Third, the models do not control for household income. Ewing and Rong (2008) find a statistically significant relationship between household energy use and income levels. Housing form is considered to be demand-driven. Building multi-family housing that would draw the current buyers of detached single-family housing would likely involve building that multi-family housing into bigger homes, building it with bigger appliances, and populating it with people who a) have more money and b) put fewer people per room into each unit(Clark & Berry, 1995). These factors all suggest that the real-world impact of policies to effect changes in housing form would have smaller results than the models in this analysis predict.

However, because these additional characters would likely also correlate strongly with the median number of rooms per housing unit, it is likely that by controlling for median rooms in the housing stock of each MSA, some of these issues are controlled for, if imperfectly. Previous research done by Ewing(2008) are able to control for housing size in their measurement of its impact on household energy use, but as Randolph (2008) points out, they do not control for it when measuring the difference between multi-unit and detached single-family housing. A better control, using room size, would be to use data taken from individual homes, as Brownstone and Golob (2009) did, and to control for housing size at the level of the individual housing unit. Ewing and Rong (2008) also specifically mention that household-level data would produce more powerful results.

Fourth, the models in this analysis do not control for other socioeconomic factors which have been found to impact energy consumption in the home. Other reports have found that race, income, family structure and type of employment all have statistically significant impacts on energy consumption (Ewing & Rong, 2008; Haas, Auer, & Biermayr, 1998; Stern & Aronson, 1984; Raaij & Verhallen, 1983). For example, it is likely that lower-income people live disproportionately in smaller or multi-unit housing(Bin & Dowlatabadi, 2005). To the extent those factors also vary with housing type, my housing variables are absorbing and expressing deeper socioeconomic effects.

Brownstone and Golob (2009), in their study of the impact of density on vehicle based energy consumption, were able to control for household income, race, and education at the level of the individual housing unit. While the authors observed no statistically significant relationship between any of those factors and transportation energy use, the results of this study models would be more reliable with better socioeconomic controls (particularly for income).

The use of climatic divisions for weather data represents an imperfect attempt at averaging the weather experience of the residents of each MSA, for two reasons. First, many MSAs or parts of MSAs are situated in the same climatic divisions as other MSAs. In some cases, this is not troubling, because the areas are likely very similar in their weather experiences. In other cases, however, it is likely that their weather experiences are different enough to impact their demand for household heating and cooling, and the data obscures that difference. Second, the data from individual weather stations is averaged to create divisional values. It is not weighted by population density, and so two weather stations in a rural area would count twice as strongly as a single station in the heart of a city. It is likely that less-populated areas are over-represented by the data collection within each MSA (there are almost certainly not as many weather stations on a per-capita basis in Manhattan as there are in eastern Long Island).

This second weather-data drawback raises another issue. If less-dense areas are over-represented in the weather analysis, then to the extent that there are temperature differences within MSAs, we are ascribing rural weather experiences to urban housing forms. As a consequence, two temperature phenomena are obscured. First, the urban heat-island effect, in which absorbed heat in densely built areas is radiated back into the atmosphere at night, will be under-represented by the weather data. Second, the "lake effect" phenomenon, where areas along the coasts of the five great lakes encounter temperatures noticeably lower than those encountered only a few miles further away during the spring and early summer, would likely be under-represented in this weather data. As a consequence, since most of the urban areas along the lake have their dense centers within the lake effect zone, the energy use by the housing in those regions is being correlated to significantly higher temperatures further out. This measurement problem matters, because of the 99 MSAs observed in this analysis, seven are prone to this specific effect. The impact on the data used for this analysis is that energy consumption in these areas appears lower than it actually would be at the recorded temperature. This may have the effect of artificially depressing the apparent energy consumption at temperatures above 65 degrees, making the cooling degree-days variable less likely to show a significant relationship to energy use. It may also have the effect of artificially increasing the apparent energy consumption at temperatures below 65 degrees. The importance of this to urban planning implications is that dense housing types, which are most likely present in greater numbers in these cooler bands, are consuming energy differently not only because of structural and socio-economic factors but possible also because of weather factors.

Finally, a more powerful analysis of the relationship between weather and emissions from energy use in the home would use panel data, with which observers could track changes in per-capita emissions over time. The use of two snapshots, from 2000 and 2005, is less informative.

No single data could provide all the needed data for this study, so this study used different data sources. The measurement errors from secondary data require caution regarding the estimates. The obtainability of more reliable and comprehensive data plays a crucial role in better results.

5.3 Conclusions

This study seeks to measure the scale of the statistical relationship between the residential energy consumption and a number of variables describing housing and urban form characteristics. It finds that a greater presence of some categories of housing stock is significantly correlated with lower household energy use. That correlation, however, does not suggest a simplistic relationship that would allow simply adding more units in building and progressively lowering energy consumption and related emissions. A greater presence of housing in buildings with over twenty units was observed to correlate with lower per-capita consumption when those units replaced detached single-family homes, and a larger presence of row housing also showed such a correlation. By contrast, a greater presence of housing in buildings with three to nineteen units did not show the same correlation.

The results of this study raise significant doubts about the approach of categorizing all multi-unit housing into a single category for analytical purposes. The results produced by such a gross categorization were relatively weak in comparison with the results produced by models using smaller sub-categories. Researchers seeking to understand the relationship of housing form to energy consumption would be served better with models and data that capture variations within the category of multi-unit housing.

This study also finds a significant relationship between household energy use and a historical pattern of intensive land conversion, which is closely related to sprawl. A history of high land-use conversion through the 1980s and 1990s, relative to total housing stock, relates to higher per-capita emissions from home energy use, even when controlling for a host of other factors. These are important results because while the literature on sprawl and energy use focuses predominantly on emissions from transportation, these results suggest that sprawl has indirect effects on energy use in the home as well.

The results of this study are limited, however, by the inability to include important controls in a way that allows the regression models to consider the impacts of housing and urban form characteristics without accidentally measuring differences in factors like occupancy patterns, income differences between housing types, size differences of units in different housing types, and other socio-economic factors shown in prior research to impact energy use. As such, this paper does not prove any major causal mechanisms, but it concludes that the literature regarding smart growth and new urbanism should expand its focus. A consideration into the relationship of urban form, especially sprawl characteristics to household energy, rather than simply considering impacts on vehicle miles traveled and auto relate energy consumption and emissions, is necessary. It is likely that failure to satisfactorily understand how urban form impacts energy use in the home, as well as energy use on the road, results in an underestimation of the potential emissions-cutting benefits of compact urban design.

Statistical analysis identified the effects of various factors on the energy consumption patterns in U.S. cities. This research also showed the trends and distributions of household energy consumption. By contributing to the understanding of the extent of the impacts that certain characteristics have on the sustainability of a city, this study contributes to a literature that can eventually provide support to planners to make environmentally friendly urban planning.

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APPENDIX A

LIST OF THE TOP 100 METROPOLITAN AREAS

1. Akron, OH
2. Albany-Schenectady-Troy, NY
3. Albuquerque, NM
4. Allentown-Bethlehem-Easton, PA-
5. Atlanta-Sandy Springs-Marietta,
6. Augusta-Richmond County, GA-
7. Austin-Round Rock, TX
8. Bakersfield, CA
9. Baltimore-Towson, MD
10. Baton Rouge, LA
11. Birmingham-Hoover, AL
12. Boise City-Nampa, ID
13. Boston-Cambridge-Quincy, MA-
14. Bridgeport-Stamford-Norwalk, CT
15. Buffalo-Niagara Falls, NY
16. Cape Coral-Fort Myers, FL
17. Charleston-North Charleston, SC
18. Charlotte-Gastonia-Concord, NC-
19. Chattanooga, TN-GA
20. Chicago-Naperville-Joliet, IL-IN-
21. Cincinnati-Middletown, OH-KY-IN
22. Cleveland-Elyria-Mentor, OH
23. Colorado Springs, CO
24. Columbia, SC
25. Columbus, OH
26. Dallas-Fort Worth-Arlington, TX
27. Dayton, OH
28. Denver-Aurora, CO
29. Des Moines, IA
30. Detroit-Warren-Livonia, MI
31. Durham, NC
32. El Paso, TX
33. Fresno, CA
34. Grand Rapids-Wyoming, MI
35. Greensboro-High Point, NC
36. Greenville, SC
37. Harrisburg-Carlisle, PA
38. Hartford-West Hartford-East Hartford,
39. Honolulu, HI
40. Houston-Baytown-Sugar Land, TX
41. Indianapolis, IN
42. Jackson, MS
43. Jacksonville, FL
44. Kansas City, MO-KS
45. Knoxville, TN
46. Lancaster, PA
47. Lansing-East Lansing, MI
48. Las Vegas-Paradise, NV
49. Lexington-Fayette, KY

50. Little Rock-North Little Rock, AR
51. Los Angeles-Long Beach-Santa Ana, CA
52. Louisville, KY-IN
53. Madison, WI
54. Memphis, TN-MS-AR
55. Miami-Fort Lauderdale-Miami Beach, FL
56. Milwaukee-Waukesha-West Allis, WI
57. Minneapolis-St. Paul-Bloomington, MN-WI
58. Nashville-Davidson--Murfreesboro, TN
59. New Haven-Milford, CT
60. New Orleans-Metairie-Kenner, LA
61. New York-Northern NJ-Long Island, NY-NJ-PA
62. Oklahoma City, OK
63. Omaha-Council Bluffs, NE-IA
64. Orlando, FL
65. Oxnard-Thousand Oaks-Ventura, CA
66. Palm Bay-Melbourne-Titusville, FL
67. Philadelphia-Camden-Wilmington, PA-NJ-DE-
68. Phoenix-Mesa-Scottsdale, AZ
69. Pittsburgh, PA
70. Portland-South Portland-Biddeford, ME
71. Portland-Vancouver-Beaverton, OR-WA
72. Poughkeepsie-Newburgh-Middletown, NY
73. Providence-New Bedford-Fall River, RI-MA
74. Raleigh-Cary, NC
75. Richmond, VA
76. Riverside-San Bernardino-Ontario, CA
77. Rochester, NY
78. Sacramento--Arden-Arcade--Roseville, CA
79. Salt Lake City, UT
80. San Antonio, TX
81. San Diego-Carlsbad-San Marcos, CA
82. San Francisco-Oakland-Fremont, CA
83. San Jose-Sunnyvale-Santa Clara, CA
84. Sarasota-Bradenton-Venice, FL
85. Scranton--Wilkes-Barre, PA
86. Seattle-Tacoma-Bellevue, WA
87. Springfield, MA
88. St. Louis, MO-IL
89. Stockton, CA
90. Syracuse, NY
91. Tampa-St. Petersburg-Clearwater, FL
92. Toledo, OH
93. Trenton-Ewing, NJ
94. Tucson, AZ
95. Tulsa, OK
96. Virginia Beach-Norfolk-Newport News, VA-NC
97. Washington-Arlington-Alexandria, DC-VA-MD-
98. Wichita, KS
99. Worcester, MA
100. Youngstown-Warren-Boardman, OH-PA