ABSTRACT

Title of Dissertation:	**IMPACT OF URBAN SPRAWL ON U. S. RESIDENTIAL ENERGY USE**
	Fang Rong, Doctor of Philosophy, 2006
Dissertation Directed By:	Professor Matthias Ruth School of Public Policy

Improving energy efficiency through technological advances has been the focus of U.S. energy policy for decades. However, there is evidence that technology alone will be neither sufficient nor timely enough to solve looming crises associated with fossil fuel dependence and resulting greenhouse gas accumulation. Hence attention is shifting to demand-side measures. While the impact of urban sprawl on transportation energy use has been studied to a degree, the impact of sprawl on non-transport residential energy use represents a new area of inquiry. This dissertation is the first study linking sprawl to residential energy use and provides empirical support for compact land-use developments, which, as a demand-side measure, might play an important role in achieving sustainable residential energy consumption.

This dissertation develops an original conceptual framework linking urban sprawl to residential energy use through electricity transmission and distribution losses and two mediators, housing stock and formation of urban heat islands. These two mediators are the focuses of this dissertation.

By tapping multiple databases and performing statistical and geographical spatial analyses, this dissertation finds that (1) big houses consume more energy than small ones and single-family detached housing consumes more energy than multi-family or single-family attached housing; (2) residents of sprawling metro areas are more likely to live in single-family detached rather than attached or multifamily housing and are also expected to live in big houses; (3) a compact metro area is expected to have stronger urban heat island effects; (4) nationwide, urban heat island phenomena bring about a small energy reward, due to less energy demand on space heating, while they impose an energy penalty in States with a hot climate like Texas, due to higher energy demand for cooling; and taken all these together, (5) residents of sprawling metro areas are expected to consume more energy at home than residents of compact metro areas.

This dissertation concludes with the policy implications that emerged from this study and suggestions for future research as well.

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IMPACT OF URBAN SPRAWL ON U. S. RESIDENTIAL ENERGY USE

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

To my parents and my husband

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I want, particularly, to acknowledge Dean of the School Public Policy Professor Steve Fetter's contribution to my work. He helped me include the formation of urban heat islands as an important part of the conceptual framework of this dissertation and put me in touch with Meteorology faculty member Professor Eugenia Kalnay for both the climate data and the methodology to measure the effects of urban heat islands.

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Chapter 1: Introduction

1. 1 Statement of the Problem

      Since the beginning of our short oil era around 1860, the world population has increased dramatically. This population growth has been fueled substantially by cheap oil. However, with fossil fuel resources becoming scarce and production already declining in all but a few major oil regions, peak oil is an emerging reality, the point at which worldwide oil production will peak and then decline in the face of growing energy demand (Bentley 2002; Greene and Hopson 2003; Bakhtiari 2004).

      In 1970, U.S. oil output first peaked and since then has begun a long decline. After that, the world experienced several oil price spikes or even crises. On October 19, 1973, an Arab oil embargo began that doubled crude oil price to $40 per barrel; the conflict between the United States and Iran pushed the price of crude oil to an all-time high at over $90 per barrel at the end of 1979 (all prices are in January 2006 dollars); and another oil spike occurred when the UN-endorsed coalition invaded Iraq in the early 1991 (Bahree 2006).

      The recent oil price spike rekindled concerns about the worldwide peaking of oil production. The price of crude oil almost tripled in three years and reached a record price of $75.35 per barrel on April 21, 2006. Gasoline prices also reached an all-time high at an average $3 per gallon during the first week of September 2005 in the aftermath of Hurricane Katrina (DOE 2005).

Although there is no consensus on when peaking will occur, few people would disagree that the balance between energy supply and demand is more fragile than ever before. Demand is increasing not only in the United States, which currently accounts for one-quarter of all petroleum consumption worldwide, but also in developing counties, including India and especially China, which are adopting western-style car cultures and expanding their manufacturing bases (Crompton and Wu 2005). A severe global recession may be triggered when peaking of oil production occurs (Attarian 2002; Tharakan et al. 2004)

In addition, there is an emerging scientific consensus that greenhouse gas accumulations due to human activities are contributing to global climate change with potentially catastrophic consequences (IPCC 1996; Greenough, McGeehin et al. 2001; Barnett and Adger 2003). Although it is impossible to say that any particular extreme weather event such as a hurricane, flood, or drought is a result of global climate change, the record number of named storms in the Atlantic in 2005, including Hurricanes Katrina, Rita, and Wilma, raised the chilling possibility that extreme weather events are becoming more common, in part due to global warming (Trenberth 2005). As of September 2005, a total of 156 countries have ratified the Kyoto Protocol, a binding treaty that commits the industrialized nations to reduce greenhouse gas emissions, principally carbon dioxide, to below 1990 levels. The United States and Australia, however, are the two notable exceptions that did not sign the Protocol.

Within this larger picture, the importance of reducing energy use in the residential sector stands out. In 2004 the U.S. residential sector consumed more than

21 quadrillion Btu of energy, accounting for more than one fifth of the total primary energy consumption in the United States (EIA 2005a). The sector also produces more than one fifth of the total U.S. energy-related carbon dioxide emissions, approximately 1,215 million metric tons per year (EIA 2004a).

   To address the problem of the limited energy supply and the continuously increasing energy demand, in past decades we have almost exclusively relied on technological advances (Siderius 2004). However, increasing energy efficiency achieved through technological advances just means more service delivered per fixed amount of energy consumed and does not necessarily mean less energy consumed. If the rate of increase in energy efficiency fails to keep pace with the rate at which demand for energy service grows, per-capita energy use will continue to rise. There is already evidence that advances in technology alone will be neither sufficient nor timely enough to achieve a sustainable growth in residential energy use. For example, as shown in Figure 1, despite increasing energy efficiency, the total residential primary energy use per capita has been gradually increasing since the early 1980s, and the total residential carbon dioxide emissions per capita have also been gradually increasing since the early 1990s.

Figure 1: Total Residential Energy Use Per Capita and Associated Per-Capita Carbon Dioxide Emissions Released (Source: DOE, 2005)
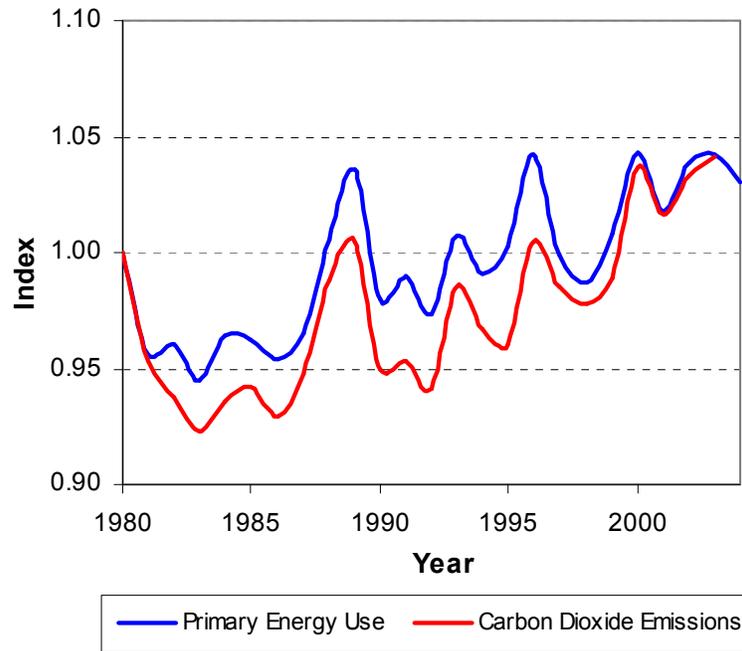
Efficiency gains may trigger more energy use, which negates some or all of the benefits of greater energy efficiency, the so-called rebound effect (Greening, Green et al. 2000; Lebot, Bertoldi et al. 2004). Some researchers argue that energy efficiency can play only a minimal role in meeting future energy needs (Lightfoot and Green 2001), and that historic increases in the energy efficiency cannot be sustained into the future (Siderius 2004). All these suggest that demand-side measures will be required to keep supply and demand in reasonable balance (Kunkle, Lutzenhiser et al. 2004; Lebot, Bertoldi et al. 2004; Siderius 2004).

Meanwhile, urban sprawl has become the dominant urban development pattern in the United States over the past few decades (Ewing, Pendall et al. 2002). More and more people and jobs are leaving cities for scattered locations in outlying

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areas, residential and commercial areas are widely separated, the network of roads is marked by huge blocks and poor access, people have to rely on automobiles for access to jobs and services, and the pedestrian environment is inhospitable (Ewing 1997; EPA 2001; Galster, Hanson et al. 2001; Ewing, Pendall et al. 2002).

A great deal of attention has been paid to the various costs of urban sprawl in the United States, including higher transportation energy use, air pollution, loss of resource lands, and higher infrastructure and service costs (EPA 2001; Burchell, Lowenstein et al. 2002; Ewing, Pendall et al. 2002). Many studies have suggested that energy use in the transportation sector, a sector sharing many common features with the residential sector, could be significantly reduced through implementing improved land-use planning (EPA 2001; Holtzclaw, Clear et al. 2002; Biirer, Goldstein et al. 2004). While the impact of urban sprawl on transportation energy use has been studied to a degree, the impact of sprawl on residential energy use represents a new area of inquiry. This dissertation attempts to fill the blank field.

1. 2 Purpose of the Dissertation

The purpose of this dissertation is to explore the dynamics by which urban sprawl could affect residential energy use and thus to provide a better understanding of whether or not we could reduce residential energy use by the implementation of improving urban land-use planning. To achieve this purpose, this dissertation surveyed the literature related to both residential energy use and urban sprawl and set up the conceptual framework to link sprawl to residential energy use. According to this framework, there are three links between urban sprawl and residential energy use.

The first one is directly through electricity transmission and distribution (T&D), the second one is indirectly through housing stock, and the third one is indirectly through the formation of urban heat islands (UHI). Compared to the two indirect links, the impact of the first link might be negligible, because electricity T&D losses only account for less than 7 percent of the total electricity generated in the United States (IEA 2004) and much of these losses occur whether the electricity is distributed to compact or sprawling population centers. The two indirect links, therefore, are the focuses of this dissertation.

1. 3 Research Questions

The objective of this dissertation is to provide an original understanding of how urban sprawl might affect residential energy use. To achieve this goal, this dissertation addresses the following five sub-questions:

- *What is the impact of housing unit characteristics including house size and type on residential energy use?*
- *What is the impact of urban sprawl on housing stock?*
- *Do we experience urban heat island phenomena?*
- *Do urban heat island phenomena affect residential energy use? If so, do they impose an energy reward or an energy penalty?*
- *What is the impact of urban sprawl on urban heat island formation?*

The answers to the first two sub-questions, taken together, could enable us to link urban sprawl to residential energy use through the indirect link of housing stock.

The answers to the last three sub-questions, taken together, could enable us to link urban sprawl to residential energy use through the indirect link of urban heat island formation. The answers to the five sub-questions, taken together, could finally solve the interest of this dissertation; that is, the potential impact of urban sprawl on residential energy use.

1. 4 Significance of the Dissertation

This dissertation is the first integrated study on residential energy use and urban land-use patterns. The research into sustainable energy use has paid a great deal of attention in past decades to the improvement of energy efficiency to solve looming crises associated with fossil fuel dependence and resulting greenhouse gas accumulation. We design high-R-value walls and ceilings and seek out high-efficiency equipment and appliances, but we too often overlook an equally important consideration, where and how we live, which affects how much energy we consume at home. Meanwhile, the research into urban developments and smart growth focuses on changes in land use and transportation in order to improve the quality of life of local populations within the broader contexts of social, economic and environmental change, but it still leaves a blank field unplowed, which is, the energy use in the residential sector.

First, this dissertation contributes to this new field by proposing an original conceptual framework that discloses the dynamics by which urban sprawl or urban land-use patterns could affect residential energy use. This conceptual framework not

only guides all the analyses in this dissertation, but provides a good applicable structure for future research into urban land-use and residential energy use.

Second, this dissertation provides instructive answers to the impact of urban sprawl on residential energy use, and expands the policy debate on sustainable energy use and smart growth. In particular, this dissertation provides empirical support for the important role of smart growth, as a demand-side measure, in achieving sustainable future residential energy consumption.

Last, this dissertation provides an original understanding of the impact of urban sprawl on metropolitan areas' housing stock, and creates new knowledge on urban heat island phenomena. It is the first empirical study, for example, addressing the question of whether or not urban heat island phenomena impose an energy penalty at the national level. It is also the first empirical study that links urban sprawl to urban heat island formation at the national level.

1. 5 Organization of the Dissertation

The organization of this dissertation is as follows. After this introduction, chapter 2 reviews the literature related to both urban sprawl and residential energy use. Special attention is paid to the major factors affecting residential energy use, the methodologies used to measure sprawl, the impact of urban developments on the formation of urban heat islands, and the impact of urban heat island phenomena on residential energy use. Based on the literature review and synthesis, an original conceptual framework is developed in this chapter to provide a theoretical foundation to guide the analyses of this dissertation.

Chapter 3 examines the relationship among urban sprawl, housing stock, and residential energy use. Section 3.1 details the data used, including not only disaggregate household-level data on energy use, household characteristics, and housing unit characteristics, but aggregate county-level data on the degree of sprawling within counties and aggregate metropolitan-level data on the size of metropolitan population and residential construction cost. In particular, the section discusses the data sources and collection methods. Section 3.2 presents the research methods utilized in this study. This section first argues that hierarchical models are better than ordinary least squares models in this study to link urban sprawl to housing stock, and then describes the specifications for all three models respectively used to link house type and size to residential energy use, to link urban sprawl to house type, and to link urban sprawl to house size. Section 3.3 first provides a snapshot on how residential primary energy use differs by house type, house size, and the year built, and then presents the regression findings on the dependence of residential primary energy use on the characteristics of housing units. Section 3.4 moves on to explore the impact of urban sprawl on households' choices of house type. This section first presents a nationwide picture on how housing mix, shares of single-family detached, single-family attached, and multifamily housing, differs across U.S. metropolitan counties, and then describes the regression results of hierarchical nonlinear models, which regress the trichotomous outcome, house type, by controlling for both household characteristics at household level and place-specific characteristics. Section 3.5 continues to explore the impact of urban sprawl on households' demands for floor areas, first with a nationwide picture on how the median house size differs

across U.S. metropolitan counties, and then with the regression findings of a hierarchical linear model on the continuous outcome, house size. Section 3.6 closes this chapter with a general conclusion on how urban sprawl could affect residential energy use through its impact on housing stock by synthesizing the two findings from section 3.4 and 3.5.

Chapter 4 examines the relationship among urban sprawl, urban heat island formation, and residential energy use. Section 4.1 discusses the data sources, collection methods, and manipulated techniques. The data used in this chapter include temperatures, space-conditioning energy use, characteristics of households and housing units, county sprawl index, and other geographic spatial data. Section 4.2 presents the research methods utilized in this study. This section first briefly introduces what is a degree-day approach, then discusses the methodology used to quantify the urban heat island intensities, and finally describes the statistical approaches to link degree-days to space-conditioning energy use and the approaches to link urban sprawl to the urban heat island intensities as well. The following sections then present the major findings. Section 4.3 explores whether or not nationwide urban cities experience higher temperatures than their surrounding rural areas. Section 4.4 discusses whether urban heat island phenomena impose an energy reward or penalty. Section 4.5 examines the relationship between the urban heat island intensity and the degree of sprawling. Section 4.6 closes with a general conclusion on how urban sprawl could affect residential energy use through its impacts on urban heat island formation by synthesizing all the findings from sections 4.3, 4.4, and 4.5

Chapter 5 closes with a concluding chapter. Section 5.1 summarizes the two findings from chapters 3 and 4 which, respectively, explore the impact of urban sprawl on residential energy use through two mediators, housing stock and urban heat island. Section 5.2 then synthesizes the two findings and provides a general conclusion on the impact of sprawl on residential energy use. Section 5.3 discusses important policy implications that emerged from this dissertation. Section 5.4 provides recommendations for future research.

Chapter 2: Linking Urban Sprawl to Residential Energy Use

2.1 Studies on Residential Energy Use

2. 1. 1 Overview of Residential Energy Use

The residential sector is a key U.S. energy demand sector and an important source of energy-related carbon dioxide emissions.   In 2004 the U.S. residential sector consumed more than 21 quadrillion Btu of primary energy in total, which accounted for over one fifth of the total U.S. energy demand and increased by more than 400 percent from fifty years ago (EIA 2005a). The sector also produces more than one fifth of total U.S. energy-related carbon dioxide emissions, approximately 1,215 million metric tons per year (EIA 2004a).

The U.S. residential sector is experiencing an increasing trend of electrification. While natural gas is a principal energy source used in U.S. residential buildings, accounting for about half of the total delivered energy consumption in 2004, the share of electricity has been steadily increasing from roughly 10 percent in the 1950s to approximately 40 percent today (EIA 2005a). As shown in Figure 2, the per capita use of natural gas and fuel oil both peaked in the early 1970s and since then both have been gradually decreasing, while per-capita electricity use has been dramatically increasing by almost ten times in the past five decades, from 1.6 million Btu of delivered energy in 1950 to 15 million in 2004.   Residential electricity demand surpassed fuel oil demand in the late 1970s, becoming the second most used

energy source, and is projected to match natural gas demand around 2020, becoming the most used energy source (EIA 2005a).

Figure 2: Historical Record of Residential Delivered Energy Use (Source: EIA 2005a)
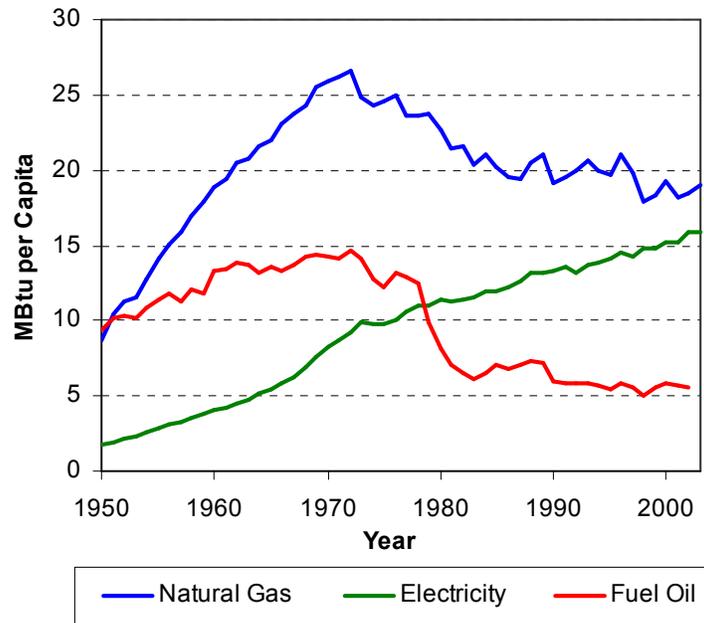
Increasing electrification has been a function of an increasing deployment of cooling technology, electricity-fueled heating applications, and appliances such as personal computers or information technology.

The mix of residential energy end-uses is also experiencing a dynamic change. Energy is mainly used in residential buildings for space heating, cooling, water heating, lighting, home appliances, etc. The largest proportion of delivered energy used now is for space heating (see Figure 3), but the share of the total has decreased from 56 percent in the early 1980s to 46 percent in 2001. During the same period, the share of energy consumption for cooling has increased from 4 percent to 6 percent.

The share of energy consumption for appliances is also significantly increasing in the period due to electrification of homes (EIA 2004b) and is projected to surpass space heating and become the primary end-use around 2035 (Rong, Clarke, et al. 2006).

Figure 3: Residential Delivered Energy Use by End-Use, 2001 (Source: EIA, 2004b)
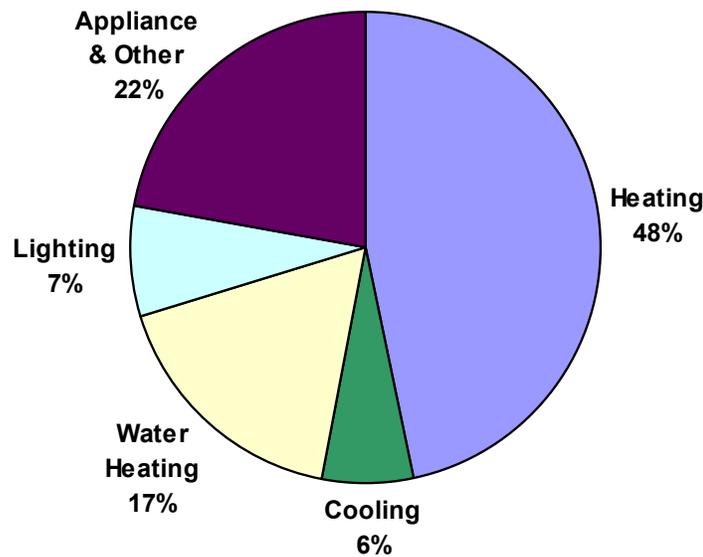
2. 1. 2 Factors Influencing Residential Energy Use

People do not demand energy; they demand goods and services that require energy: warm homes in the winter, cool homes in the summer, cooked food, stored perishable food (through refrigeration), access to internet, television, and so forth. To understand what factors affect residential energy use, it is useful to consider the counteracting forces that ultimately drive residential energy use. The equation below is a simple heuristic identity intended to illustrate the drivers behind energy demand.

$$Energy = \left[population \right] \left[\frac{floorspace}{population} \right] \left[\frac{Service}{Floorspace} \right] \left[\frac{Energy}{Service} \right]$$

In this equation, energy use is a function of four terms. The evolution of residential energy use will depend on the combined effects of the four elements. The derivative of the first term with respect to time, population, currently has a positive sign and this will probably continue for several decades and perhaps beyond. The U.S. Census Bureau projects that the total U. S. population will increase by 50 percent from 0.29 billion today to 0.42 billion in 2050.

The derivative of the second term, floor space per capita, currently also has a positive sign and this will also probably continue for several decades. The average U.S. household size has been steadily declining, while the average home has become increasingly larger. According to the U.S. Census Bureau, in 1990 an average household consisted of over 4.5 people, in 1940 it was about 3.5, and by 2000 it had declined to less than 2.5. In 1940 there are less than 10 percent of households consisting of people living alone, currently over a quarter of households have been single-person.   At the same time, new houses have been getting larger. Over the past 30 years, the median floor area of new houses has almost increased by 50 percent. The size of new houses in 2005 increased to 2,433 square feet on average from 2,349 square feet in 2004, according to the National Association of Home Builders (NAHB). That is up from 2,095 square feet in 1995, 1,905 square feet in 1987 and a mere 1,660 in 1973. Additionally, there is a notable shift in the distribution of housing units away from the northern states towards the southern and western areas of the United States, which may lead to more energy demand for summertime cooling

in future while less for wintertime heating. The housing stock is a key determinant of the total energy use in the residential sector. The evolution of residential energy use will be largely dependent on whether or not the current trend of increasing per-capita floor area will continue into the future and dependent on how the housing units will distribute.

Unlike the first two, the direction of the change in the third element, service demand per floor space, is ambiguous. Some service demands have been increasing; whereas others have been relatively flat. The energy demands for appliances, personal computers or other similar information services have been steadily increasing; whereas the energy demand for hot water has remained unchanged (Rong, Clarke, et al. 2006). The growth in appliances and information services can be attributable to the increasing penetration and the use of these dominantly-electric demands. In 1970s, numerous appliances that are a normal part of contemporary American life simply did not exist or were rarely used. Among these appliances were cordless telephones, telephone answering machines, large-screen televisions, microwave ovens, personal computers, VCRs, and DVD players. Today, the percentage of housing units using these appliances is not insubstantial (Laurence 2004).

The first three terms are all demand-side factors, while the final term, a measure of energy efficiency, is a supply-side factor, which currently has a negative derivative. The efficiencies of appliances/equipment, such as furnaces, room/central air conditioning equipment, water heaters, refrigerators, etc., have been significantly improving and have allowed American consumers to receive building services with

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lower energy requirements. For example, a standard measure of air-conditioning

equipment efficiency is the Seasonal Energy Efficiency Ratio (SEER). For a given

piece of equipment, the higher the SEER, the greater is its efficiency and the lower is

its electricity consumption. The average SEER of central air-conditioning equipment

sold in 1978 was 7.34. In 1997 the average SEER was 10.66, indicating a significant

improvement in the efficiency of air-conditioning equipment (EIA 2000).

While simplistic, this equation illuminates a meaningful dynamic in

residential energy use. Limiting the growth in residential energy use can be viewed

as a competition between population growth, per-capita floor space growth, and

emerging growth from information services and etc. that drive service demands, on

the one hand, and advances in the technologies that use energy to provide these

demands, on the other. Currently, advances in the technologies can hardly compete

with the demand growth from increasing population, increasing floor space per

capita, and more emerging demands of information services. As shown in Figure 1 in

chapter 1, despite significantly increasing energy efficiency, residential primary

energy use per capita has been gradually increasing since the early 1980s.

2. 1. 3 Electricity Generation, Transmission & Distribution

Two types of energy are often discussed in the energy-related literature, total

primary energy and total delivered energy. According to the definitions from the U. S.

Energy Information Administration (EIA), total primary energy consists of all energy

forms, including electric utility generation and transmission losses. Total delivered

energy refers to the amount of energy delivered to the end user (e.g. buildings), but

excludes utility generation and transmission losses. So the difference between the

two types of energy is total electric utility generation and transmission loss, which has been significantly increasing in the past fifty years (see Figure 4).

Figure 4: Total Primary and Delivered Residential Energy Use (Source: EIA 2005a)
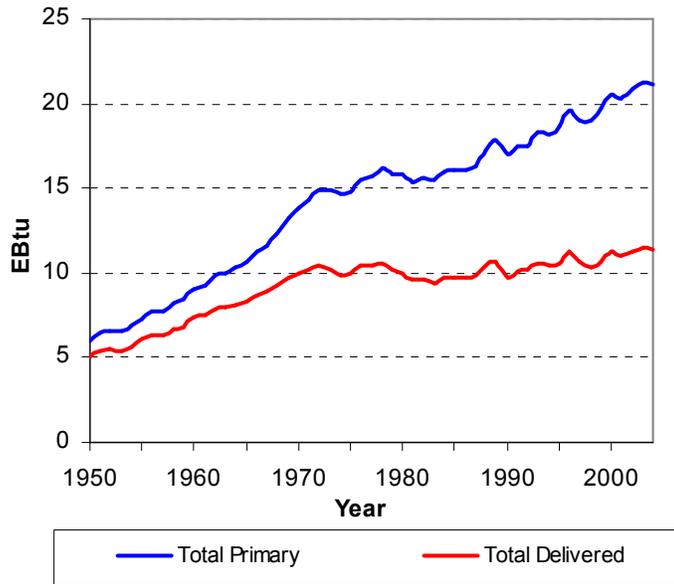
Figure 5: Per Capita Primary and Delivered Residential Energy Use (Source: EIA 2005a)
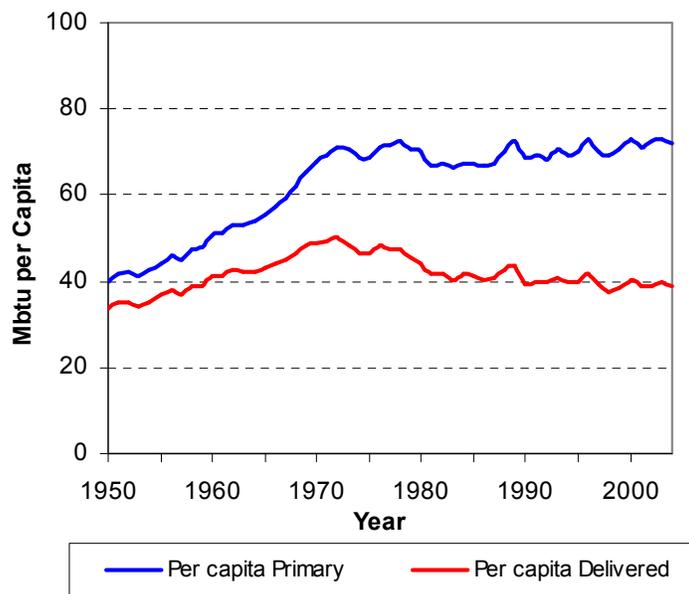
The difference between per-capita residential primary and delivered energy use has also been significantly increasing in the past fifty years. Although per-capita delivered energy use has been slightly decreasing since the early 1970s, per-capita residential primary energy use did not (see Figure 5).

There are two possible factors that could contribute to the increasing gap between the residential primary and delivered energy use or the increasing losses from electric utility generation and transmission. The first contributing factor is the efficiencies of electric utility generation and transmission. Although the total electric utility generation and transmission losses have been dramatically increasing since 1950s, the loss per unit electricity delivered has been slightly decreasing (see Figure 6) and the efficiencies of electric utility generation and transmission today have been improving from 0.27 fifty years ago to 0.45 (EIA 2005a).

Figure 6: Total Electric Utility Generation and Transmission Losses and Losses per Unit Electric Delivered to End-users (Source: EIA 2005a)
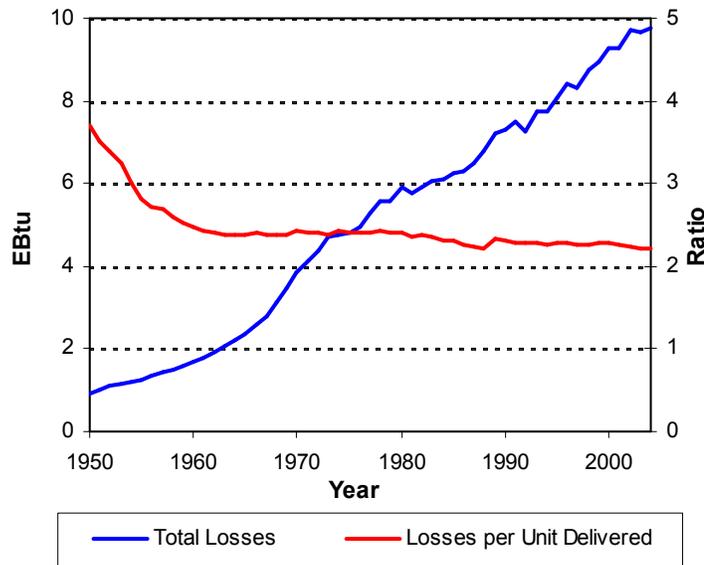
The other contributing factor is the share of electricity among the total delivered energy compared to natural gas and fuel oil. As shown in Figure 2 in the section 2.1.1, the share of electricity has been steadily increasing from roughly 10 percent in the 1950s to approximately 40 percent today, and per-capita electricity use has been dramatically increasing by almost ten times in the past five decades (EIA 2005a). There are more electricity being used, more electric losses and higher gap between primary and delivered energy use are there associated with.

To be noted, the increasing rate of total residential electricity use has recently surpassed that of new-built high-voltage transmission lines. During the 1990s, the total electricity use in U.S. residential sector has increased by 20 percent, while only about 9,500 miles of new high-voltage transmission lines were built, nearly a 7 percent increase (EIA, 2003).

In summary, although the efficiencies of electric utility generation and transmission have been improving, the improvement cannot negate all the dramatic increasing demand for electricity. Therefore, the net effect of these two factors reflects the increasing gap between the primary and delivered residential energy use. As the residential sector moves more toward the use of electricity, the divergence between delivered and primary energy is expected to continually increase.

There are four processes in the delivery of electricity to consumers: central generation, transmission, distribution, and retailing. Electrical losses are an inevitable consequence of the transfer of energy across electricity distribution networks. The losses may be higher due to urban sprawl. In rural areas or very low-density areas, where a large number of low-load consumers (single housing unit versus a significant

number of housing units) are distributed over a large area, the electricity distribution losses are higher both because of longer distance of power supply sources from the consumption center and relatively small and widely dispersed electricity loads (Suresh and Elachola 2000). The higher the density of electricity distribution networks or residential housing units, the higher is the network efficiency as long as the density does not exceed the robust threshold (EPRI 2002).

2. 2 Studies on Urban Sprawl

2. 2. 1 What is Urban Sprawl?

The U.S. urban land-use patterns have changed dramatically over the past century. In the early 1990s, urban areas tended to be compact, with a strong central business district and industrial facilities serving as large employment centers. Communities tended to be walkable and contained a mix of housing and convenient services such as stores, parks, and other activity centers (EPA 2001). In past decades, however, more and more people and jobs are leaving the denser inner-city cores for locations in widely scattered outlying areas; residential and commercial areas are widely separated; the network of roads is marked by huge blocks and poor access; people have to rely on automobiles for access to jobs and services and the pedestrian environment is inhospitable (Ewing 1997; EPA 2001; Galster, Hanson et al. 2001; Ewing, Pendall et al. 2002).

This new land-use pattern is called "sprawl," which has become the dominant urban development pattern in the United States over the past few decades (Ewing, Pendall et al. 2002). It has been facilitated by many interrelated factors, such as

significantly cheaper land and construction costs outside the city, lower property

taxes, and increasing job opportunities in the suburbs (Snyder and Bird 1998). Figure

7 and 8 show two snapshots of this new land-use development pattern.

Figure 7: An Urban Sprawl Example in Lancaster County, PA (Source: the Lancaster County Planning Commission)

Figure 8: An Urban Sprawl Example in Former Farmland North of Albany, New York (Source: Earth Imagery, Photography of John Mckeith)
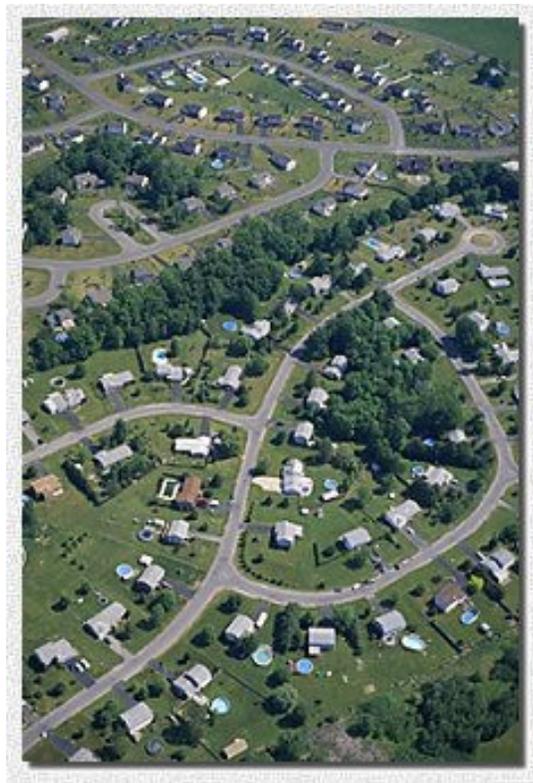
2. 2. 2 Impacts of Urban Sprawl

Some researchers have argued that sprawl has important benefits such as more mobility and privacy, lower housing costs, racial integration, and higher consumer satisfaction (Gordon and Richardson 1997; Hayward 1998; Conte 2000; Kahn 2001). In counterpoint, other researchers have depicted sprawl as a contributor to most contemporary U.S. urban and environmental problems. The suggested negative impacts of sprawl include

- Loss of resource lands (Burchell 1992; Landis 1995; Gordon and Richardson 1997; Benfield, Raimi et al. 1999) and biodiversity (Harris 1984; Kautz 1993)

- Higher infrastructure and public service costs (Frank 1989; Burchell and Listokin 1995; Ewing 1997; Burchell, Listokin et al. 1998)

- Inner-city abandonment and racial segregation (Ewing 1997; Burchell, Listokin et al. 1998; Stoll 2005)

- Weakened neighborhood social bonds because of over-dependence on automobiles (Freeman 2001) and deprivation of access for people who cannot drive or cannot afford to drive (Popenoe 1979; Kain 1992; Burchell and Schmeidler 1993)

- Higher traffic and pedestrian fatalities (STPP 1999; Ewing, Schieber et al. 2003) and higher likelihood of being obese and having high blood pressure (Lopez and Hynes 2003; McCann and Ewing 2003; Saelens, Sallis et al. 2003).

Besides all impacts listed above, two impacts of urban sprawl receive special attention in this dissertation. One is its impact on the transportation sector, and the other is its impact on housing stock. Lots of research suggests that urban sprawl will lead to an increase of motor vehicle travel (Ewing 1994; Ewing 1995; Kessler and Schroeer 1995; Burchell, Listokin et al. 1998; Bento, Cropper et al. 2003), resulting oil use (Newman and Kenworthy 1988; ECOTEC 1993; Anderson and Santore 2002), and carbon dioxide and pollution levels (Anderson, Kanaroglou et al. 1996). The research suggests that transportation energy use and greenhouse gas emissions could be significantly reduced by more compact and mixed-use developments served by efficient transit networks and walking-and-bicycling-favored microscale urban design features (Cervero 1996; Crane 1996; Newman and Kenworthy 1996; Crane and Crepeau 1998; EPA 2001; Ewing and Cervero 2001; Anderson and Santore 2002; Holtzclaw, Clear et al. 2002; Bento, Cropper et al. 2003; Biirer, Goldstein et al. 2004).

Urban sprawl may also affect a metropolitan areas' housing stock such as housing mix (single-family detached, attached, or multifamily housing) and the median house size. Unconstrained land supplies and lower land prices, often found in sprawling areas, might be associated with the shifts toward single-family detached housing, while in compact areas, constrained land supplies and higher land prices might be associated with the shift toward multifamily and single-family attached housing so as to conserve land (Nelson, Pendall et al. 2002). Meanwhile, urban sprawl might have an influential impact on a metro area's median house size. Some researchers argue that one potential benefit of sprawl was cheaper, bigger houses

(Glaeser and Kahn 2003).   Evidence for their arguments is that an average suburban

house in the United States in 1999 was 1964 square feet in size and cost $93 per

square foot, while the average center city house was 1723 square feet and cost $97

per square foot. Suburbanization, however, is different from urban sprawl. The

housing stock in two suburban areas might be different if one metro area is relatively

compact and the other is more sprawling. Moreover, theoretically speaking,

households in compact areas might consume more housing because of less spending

on transportation (STPP 2003), the so-called "substitution effect" (Katz and Rosen

1998). In short, the previous studies on sprawl and housing provide gross evidence

on the potential link between these two, but empirical analyses on the field still

represent a new area of inquiry.

2. 2. 3 How to Measure Urban Sprawl

Although urban sprawl is difficult to define and quantify, there have been a

few attempts. Several researchers (Fulton, Pendall et al. 2001; Malpezzi and Guo

2001; USA Today 2001; Lopez and Hynes 2003) have focused on density as the sole

indicator of sprawl. For example, Fulton, Pendall et al. (2001) defined density as the

"population of a metropolitan area divided by the amount of urbanized land in that

metropolitan area." They used data from surveys by the National Resources

Inventory that estimate the amount of developed land in each county. Based on the

assumption that the lower the density, the greater is the amount of sprawl, Fulton et

al. concluded that the West was home to some of the densest and the most anti-sprawl

metropolitan areas in the nation. The South and the Northeast and Midwest showed

different types of sprawl: the South is accommodating a great deal of population

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growth but is urbanizing a large amount of previously non-urban land to do so, while the slow-growing metropolitan areas in the Northeast and Midwest have consumed extremely large amounts of land for urbanization in order to accommodate very small quantities of population growth.

Lopez and Hynes (2003) proposed a measure based on both the residential density and concentration dimension of sprawl. They used 1990 and 2000 U.S. Census data, and the population density in each census tract was computed by dividing its population by its land area. For each metropolitan area, tracts were sorted into high-density tracts, low-density tracts, and rural tracts. A sprawl index (SI) score was computed for each metropolitan areas and defined as $SI_i = (((S\%_i - D\%_i)/100) + 1)) \times 50$, where SI_i is sprawl index for metropolitan area i, $D\%_i$ is percentage of the total population in high-density census tracts i, and $S\%_i$ is percentage of total population in low-density census tracts i. The index is then transformed by constants to produce a final score on a 0 to 100 scale. Lopez et al. concluded that the size of a metropolitan area is greatly associated with its degree of sprawl. Small metropolitan areas were much more likely to sprawl. They also found that the West had the highest absolute number of metropolitan areas scoring below 25 (less sprawling) and the South had the most metropolitan areas scoring above 75 (more sprawling). Their results also showed that there has been a substantial change in the level of sprawl in the United States and sprawl increased in most metropolitan areas. All these single-dimension studies, however, have failed to measure sprawl in all its complexity.

A few studies have measured sprawl as a multi-dimensional construct. Galster, Hanson et al. (2001) and Wolman, Galster et al. (2005), for example, defined

sprawl as pattern of land use that has low levels in one or more of these dimensions: density, continuity, concentration, compactness, centrality, nuclearity, diversity, and proximity. Their sprawl index relied on GIS measurements along with detailed knowledge of local conditions and thus is difficult to duplicate nationally. Additionally, their analysis focused on urbanized areas rather than metros, while the most sprawling development in many metros occurs outside urbanized areas.

Ewing, Schmid et al. (2003) estimated sprawl indices for 83 U.S. metropolitan areas and 448 counties in 1990 and 2000. During their later research, they expanded 2000 sprawl indices to 938 counties or county equivalents (e.g. independent cities). About 83 percent of U.S. population lived in the 938 counties in 2000 (Ewing, Brownson et al. 2006). Their county sprawl index incorporates six variables from the U.S. Census and the Department of Agriculture's Natural Resources Inventory to account for residential density and street accessibility. They include

- gross population density (persons per square mile)
- percentage of the county population living at low suburban densities (less than 1500 persons per square mile)
- percentage of the county population living at moderate or high urban densities (greater than 12,500 persons per square mile)
- population density in urban areas, average block size
- and percentage of blocks with areas less than 1/100 square mile (the size of a typical traditional urban block)

The six variables were combined via principal component analysis into one factor representing the degree of sprawl within the county. The factor was then normalized such that the mean value is 100, and the standard deviation is 25.

The bigger the value of the county sprawl index, the more compact the county. For 2000 sprawl indices of the 938 counties, the scores range from a high of 352 to a low of 55. At the most compact end of the scale are four New York City Boroughs (New York County with a sprawl index of 352, Kings County with a sprawl index of 264, Bronx County with a sprawl index of 251, and Queens County with a sprawl index of 219), San Francisco County with a sprawl index of 209, Hudson County in New Jersey with a sprawl index of 190, and Philadelphia County with a sprawl index of 188. At the most sprawling end of the scale are outlying counties of metropolitan areas in the Southeast and Midwest such as Jackson County in Kansas with a sprawl index of 55 and Geauga County outside the Cleveland, OH with a sprawl index of 63. The county sprawl index is skewed. In the United States few counties approach the compactness of New York or San Francisco. About 30 out of the 938 counties have sprawl indices above 125, one standard deviation above the mean.

Ewing et al.'s sprawl indices have become widely used in health-related research (Sturm and Cohen 2004; Kelly-Schwartz, Stockard et al. 2005; Plantinga and Bernell 2005).

2. 3 Studies on Urban Heat Island (UHI)

2. 3. 1 What is UHI?

Asphalt and concrete for roads, buildings, and other structures necessary to accommodate growing populations in urban areas absorb – rather than reflect – the sun's heat. The displacement of trees and shrubs eliminates the natural cooling effects of shading and evapotranspiration. On clear hot summer days, it is estimated that the air temperature in a typical city could be 1°C to 3°C hotter than the surrounding area (Rosenfeld 1995), so-called "urban heat island (UHI) effect."

The heat island sketch pictured in Figure 9 shows a city's heat island profile. It demonstrates how urban temperatures are typically lower at the urban-rural border than in dense downtown areas. The graphic also show how parks, open land, and bodies of water can create cooler areas.

Figure 9: Urban Heat Island Profile (Source: U.S. EPA Heat Island homepage)
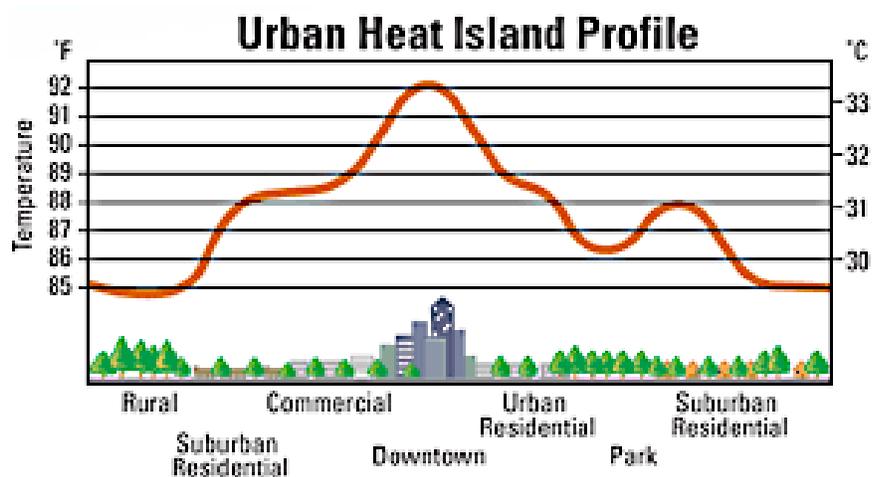
Empirical evidence of urban heat islands exists for many mega-cities across the United States, such as New York City (Gedzelman, Austin et al. 2003), Phoenix (Balling, Skindlov et al. 1990), Atlanta (Bornstein and Lin 2000), Washington DC, and Los Angeles (Taha 1997). It also exists for many international mega-cities, such as Athens (Santamouris, Papanikolaou et al. 2000), Mexico City (Jauregui 1997), Japan (Hadfield 2000), and Singapore (Wong, Tay et al. 2003). Although the name of urban heat island implies that it is solely an urban problem, research has shown urban heat islands are also becoming prevalent in small cities (Pinho and Orgaz 2000) and suburbs (Stone and Rodgers 2001).

2. 3. 2 How to Measure UHI Intensities

A traditional methodology to estimate the magnitudes of heat island effects is to compare observations in cities with those in surrounding rural areas (Lowry 1977; Pon, Stamper-kurn et al. 2000). However, the results might differ significantly depending on whether population data or satellite measurements of night-light are used to classify urban and rural areas (Kalnay and Cai 2003). To get the synoptic weather[1], stations in rural area should be close enough to the city so that rural climate readings may characterize the urban area, yet these stations should also be distant enough from the city to be free of urban influences. Moreover, all stations to be compared must either be located in areas with identical microclimates or absence of

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[1] synoptic weather observation refers to a surface weather observation, made at periodic times (usually at three-hourly and six-hourly intervals specified by the World Meteorological Organization), of sky cover, state of the sky, cloud height, atmospheric pressure reduced to sea level, temperature, dewpoint, wind speed and direction, amount of precipitation, hydrometeors and lithometeors, and special phenomena that prevail at the time of the observation or have been observed since the previous specified observation.

significant microclimate effects (Pon, Stamper-kurn et al. 2000). All these make any reliable urban-rural comparisons even more intractable.

Another different approach documented is to compare the difference between the observed surface temperatures and the corresponding values derived from the NCEP-NCAR (National Centers for Environmental Prediction/National Center of Atmospheric Research) 50-year Reanalysis (NNR) (Kalnay and Cai 2003). The NCEP/NCAR reanalyses, which are currently available back to 1948, contain several meteorological parameters in a global spatial resolution of 2.5° x 2.5° (latitude x longitude) and in a vertical extend from the surface toward the 10 hPa level. They are a composite of different data sources such as land station and ship observations, satellite observations and numerical weather forecasts, which are assimilated in an AGCM (Atmospheric Global Circulation Model) and reanalyzed by means of a "frozen" state of an AGCM back to 1948. More information about the collection procedure of the NCEP/NCAR reanalyses can be found in Kalnay et al. (1996)

The NNR-determined temperature data is insensitive to urbanization or land-use effects, although it will show climate changes to the extent that they affect the observations above the surface. Therefore, there is no need to classify urban and rural areas or worry about whether climate readings from a rural station can be used as readings of synoptic weather, which makes it possible to obtain heat island effects for a large number of cities or areas.

2. 3. 3 Natural Factors Affecting UHI

A number of natural factors contribute to the occurrence and magnitudes of urban heat islands. These not only include natural factors such as weather,

geographic location, time of day and season, which are briefly discussed in this section, but anthropogenic factors such as urban designs or layouts, which are potentially more important and are discussed in the next section.

Weather, particularly wind and cloud, influences formation of heat islands. Heat island magnitudes are largest under calm and clear weather conditions. It decreases with increasing wind speed and increasing cloud cover (Kidder and Essenwanger 1995; Figuerola and Mazzeo 1998; Magee, Curtis et al. 1999; Morris, Simmonds et al. 2001; Unger, Sumeghy et al. 2001)

Geographic location influences urban heat island formation by affecting the climate and topography of the area as well as the characteristics of the rural surroundings of the city. Heat island magnitudes, for example, tend to increase from low to high latitude (Wienert and Kuttler 2005). Where cities are surrounded by wet rural surfaces, slower cooling by these surfaces can reduce heat island magnitudes, especially in warm humid climates (Oke, Johnson et al. 1991).

Time of day or season play a role, too. Urban heat island intensities most likely increase in the summer or warm half of the year, because of the greater solar energy input and lower wind speeds (Klysik and Fortuniak 1999; Philandras, Metaxas et al. 1999; Morris, Simmonds et al. 2001). The time of maximum heat island magnitude varies, but is usually a few hours after sunset (Oke 1987).

However, several challenges to the above generalizations have been mounted. For example, the greatest urban–rural difference detected in Birmingham, UK, occurs in spring and autumn (Unwin 1980). Reykjavik, Iceland, shows a tendency for negative heat island intensities (rural areas warmer than urban areas) in summer and

only weak development at other times of the year (Steinecke 1999). A larger rate of growth of Prague's urban heat island is detected since the 1920s in winter and spring rather than in summer (Brazdil and Budikova 1999).

2. 3. 4 Impacts of Urban Developments on UHI

The world has experienced rapidly growing urbanization in recent decades. In 1800 only 3 percent of the world's population lived in urban areas. By 1900 almost 14 percent were urbanites. In 2003 about 48 percent of the world's population lived in urban areas. It is expected that 61 percent of the world population will be urban by 2030 (United Nations 2004). In general, urbanization favors heat island formation by:

- Replacing natural surfaces by impervious or waterproofed surfaces, leading to a drier urban area, where less water is available for evaporation, which offsets heating of the air (Taha and Meier 1997);
- Using relatively dense building materials and lower albedo materials that are slow to warm and cool and store a lot of energy (Taha 1997);
- And generating large amount of anthropogenic heat, or heat generated from human activities, and primarily fossil fuel combustion (Taha 1997; Sailor and Lu. 2004).

Different urban development patterns might have different effects on the formation of urban islands. The larger and denser a city, the greater the urban-rural temperature difference is commonly observed (Park 1986; Yamashita, Sekine et al. 1986; Hogan and Ferrick 1998; Torok, Morris et al. 2001). From this perspective,

therefore, compact urban areas, commonly denser areas, might be more likely to favor heat island formation than sprawling areas.

However, sprawling urban areas, commonly less dense areas, are often associated with higher motor vehicle travel (Ewing 1994; Ewing 1995; Kessler and Schroeer 1995; Burchell, Listokin et al. 1998; Bento, Cropper et al. 2003) and resulting higher fossil fuel combustion (Newman and Kenworthy 1988; ECOTEC 1993; Anderson and Santore 2002). These anthropogenic heat, or heat generated from human activities, is one important factor linking to heat island formation (Sailor and Lu. 2004).

Moreover, there is empirical evidence showing that lower density patterns of residential developments are less thermal efficient than are higher density patterns and contribute more excess radiant energy per single-family residential parcel to surface heat island formation (Stone and Rodgers 2001). Although larger parcels tend to dedicate a greater proportion of the lot to tree canopy cover, these lots tend to have a greater share of un-canopied area as well.

Last, not only developments in the core of an urban area but at the urban periphery can be expected to elevate air temperatures throughout a metropolitan region (Stone and Rodgers 2001). Golany (1996) illustrates the theorized movements of heat and air within an urban heat island: under calm conditions, the highly impervious urban core acts as a regional thermal engine, causing heated air at the city center to rise and drawing in cooler air from the urban periphery. As natural lands covers at the urban periphery are converted to urban land uses, both surfaces and air temperatures in these areas increase, which ultimately increases the

temperature of the air drawn toward the city center. Consistent with this finding, research shows that the projected trends in suburban and exurban sprawl in Newark illustrate that the urban heat island phenomenon will continue to spread spatially into the future (Solecki and Rosenzweig 2003).

2. 3. 5 Impact of UHI on Residential Energy Use

Urban heat islands have a range of negative impacts on urban populations. They may directly impact human health by exacerbating the affects of summer heat waves, especially in regions with hot summers, and by providing conditions suitable for the spread of vector-borne diseases (Changnon, Kunkel et al. 1996; McMichael 2000). They may degrade local air quality by increasing the formation of urban smog, because both emissions of precursor pollutants and the atmospheric photochemical reaction rates increase (Rosenfeld, Akbari et al. 1995; Stone 2006). They may trigger adverse meteorological events such as thunderstorms by affecting precipitation events either over, or downwind of, communities (NASA 1999; Hadfield 2000).

They may also affect residential energy use by increasing the energy demand for summertime cooling and decreasing the energy demand for wintertime heating. A few studies suggest that the net effects of heat islands are mostly seen being an energy penalty rather than an energy reward. Landsberg (1981) and Taha, Douglas et al. (1997), for example, compared heating and cooling degree-days for several American cities and at airports outside them. Heating degree-day (HDD) and cooling degree-day (CDD) are quantitative indices demonstrated to reflect demand for energy to heat or cool houses and businesses. They are based on how far the average

temperature departs from a human comfort level of 65 °F. Simply put, each degree of temperature above 65 °F is counted as one CDD, and each degree of temperature below 65°F is counted as one HDD. For example, a day with an average temperature of 80 °F will have 15 cooling degree days. For more details of the degree-day formulation, see the section 4.2.1. Both research concluded that the elevation of urban temperatures would likely impose a net energy penalty for many urban areas, particularly in regions with hot summers or extensively used air conditioning (see Table 1).

Table 1: Comparison of heating and cooling degree-days for urban areas and airport sites (Source: From (Taha, Douglas et al. 1997) modified after (Landsberg 1981))

Location	Heating degree-days			Cooling degree-days		
	Urban	Airport	% Diff	Urban	Airport	% Diff
Los Angeles	384	562	-32	368	191	+92
Washington DC	1300	1370	-6	440	361	+21
St. Louis	1384	1466	-6	510	469	+11
New York	1496	1600	-7	333	268	+24
Baltimore	1266	1459	-14	464	344	+35
Seattle	2493	2881	-13	11	72	+54
Detroit	3460	3556	-3	416	372	+24
Chicago	3371	3609	-7	463	372	+24
Denver	3058	3342	-8	416	350	+19

Increased energy demand, coupled with increasing energy prices, can result in greater costs to consumers. It is estimated that as much as 15 percent of the electricity consumed for cooling within Los Angeles is utilized for the sole purpose of offsetting the effects of urban heat islands (Rosenfeld and Romm 1996). The annual

energy cost of urban heat islands alone within the United States is estimated to be approximately $10 billion (Rosenfeld and Romm 1996). The importance of the energy penalty due to heat islands particularly stands out, considering the increasing use of air-conditioning because of increasing wealth and the housing shift toward south regions (Laurence 2004).

Even if average annual energy demands for summertime cooling may not change much, the anticipated increases in peak electric demand may be significant enough to warrant changes in peak load capacity planning for the region (Ruth and Lin 2006). An average temperature increase of 3°C (5.4°F) in Toronto, for example, was found to be associated with a 7 percent increase in mean peak electric demand, but a 22 percent increase in the peak electric load standard deviation (Colombo, Etkin et al. 1999). Extremely high peak electric demands place tremendous pressures on urban electrical grids, rustling in blackouts and disrupting the normal operation of urban infrastructure and services (Stone 2006).

2. 4 Setting Up Conceptual Framework

Based on the above cross-disciplinary literature review, a conceptual framework linking urban sprawl to residential energy was set up as below (see Figure 10).

Figure 10: Conceptual Framework on Impact of Sprawl on Residential Energy Use
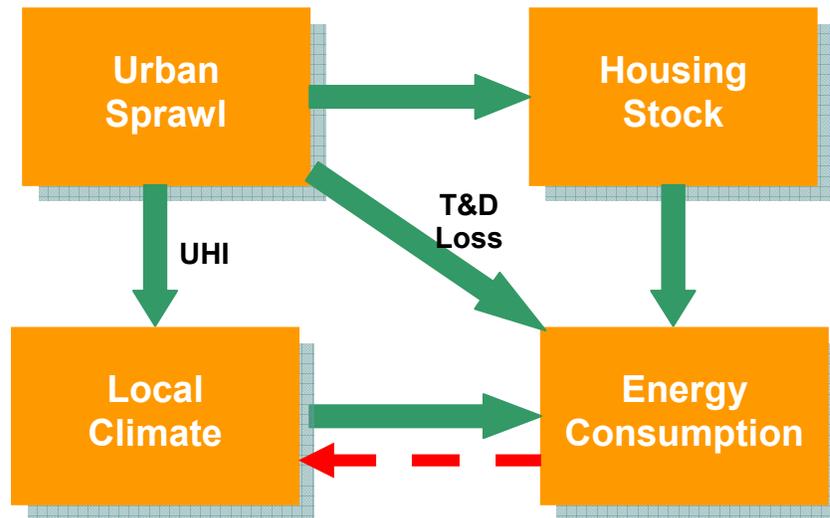
As shown in the framework, urban sprawl could have impacts on residential energy use through three links. The first link is directly through electricity transmission and distribution (T&D). In sprawling metro areas, the T&D losses might be higher because of longer distance of power supply sources from the consumption center and relatively small and widely dispersed electricity loads (Suresh and Elachola 2000). The second link is indirectly through housing stock. Energy use differs by different house types and house sizes, while sprawl could affect households' choices of housing type and house size. The last one is indirectly through the formation of urban heat islands. The energy used for space heating and cooling, which both are temperature sensitive, currently account for half of the total residential energy use. Meanwhile, urban sprawl might affect the formation of urban heat islands and thus increase urban temperatures.

Compared to the two indirect links, the impact of the first link might be negligible, because electricity T&D losses only account for less than 7 percent of the total electricity generated in the United States (IEA 2004). The two indirect links, therefore, UHI and housing stock, are focuses of this dissertation.

Chapter 3: Study on Sprawl, Housing, Residential Energy Use

3. 1 Data

The objective of this study is to first examine the dependence of residential energy use on housing unit characteristics and then to link urban sprawl to the housing stock. To achieve the first goal, we need disaggregate household-level data on energy use and the characteristics of households and housing units. To achieve the second goal, we need both disaggregate household-level data and aggregate place-specific data such as the degree of sprawling within counties.

The U.S. Energy Information Administration (EIA)'s Residential Energy Consumption Survey (RECS) provides energy data along with household and housing data for each household and thus could serve the data needs of the first purpose. Its limitations, however, in survey sample size only permit for State profiles (only four largest States) in the United States and it thus fails to serve the data needs of the second purpose. The U.S. Census Bureau's Public Use Microdata Sample (PUMS) and American Housing Survey (AHS) both contain individual household data on the characteristics of households and housing units. But different from the RECS, county residence of samples could be identified in both the PUMS and the AHS. Therefore, the PUMS and the AHS could serve the data needs of this second purpose. In addition, Ewing, Schmid et al. (2003)'s 2000 county sprawl indices were together used to achieve the second purpose as measures of the degree of sprawling within counties. The following sub-sections describe the data on energy use, households,

housing units, land-use, and other metropolitan-specific characteristics used in this study.

3. 1. 1 Energy Data

The RECS is the most comprehensive national source of residential energy use data. It is a non-random sample survey that provides energy data along with household and housing data and is restricted to housing units that are the primary residence of the occupants. The RECS was first conducted in 1978 and since 1990 the survey was conducted about every four years. This study used the RECS 2001, which is the most recent data available to the public.

The RECS 2001 obtains 4,822 housing units and represents housing units from the fifty States and the District of Columbia (EIA 2004b). It provides the total annual delivered energy consumption and total annual expenditures for each energy source by each household including natural gas, electricity, fuel oil, kerosene, and liquefied petroleum gas (LPG). It also provides such major end-use estimates on annual consumption and annual expenditures as space heating, water heating, cooling, refrigerators, and general appliances. To be noted, however, these end-use estimates are not based on data produced by placing meters on individual appliances; rather, they are obtained by estimating how much of the total annual consumption or annual expenditures for each energy source can be attributed to each of the end-use categories for each household by using a regression technique.   The end-use estimates are normalized so that the sum of the end-use estimate is equal to the actual or imputed yearly consumption or yearly expenditures for each energy source used by each household. The weighted energy price was imputed in this study based on the

information provided on the yearly energy consumption and yearly expenditures by each energy source.

Compared to fossil fuels, electricity is a high-quality energy source. One Btu of electricity is equal to about 2.3 Btu of primary energy that is used to generate electricity (EIA 2005a). Otherwise noted, this dissertation discusses the primary energy use in order to account for the difference in energy quality between electricity and natural gas or fuel oil.

Because this study focuses on single- or multi-family housing in metro areas, mobile homes and the housing units in rural areas were excluded. The final samples used in this study consist of 3,737 housing units from cities, towns, and suburbs.

3. 1. 2 Household and Housing Data

The RECS 2001 also provides data on the characteristics of households and housing units such as annual household income in dummies (e.g. household income between $40,000 to $49, 999), the number of household members including adults and the young less than sixteen years old, householders' race, house type including single-family detached, attached, or multifamily housing, house size in square footage, and house built year in dummies (e.g. house built before 1940). However, the RECS 2001 has limited sample size and does not have the necessary data coverage to make statistically valid county-level analyses for the entire United States and therefore, fails to serve the data needs of this study's second purpose to relate the degree of sprawling within counties to the county's housing stock. For the second

purpose, this study turns to the U.S. Census Bureau's Public Use Microdata Sample (PUMS) and the American Housing Survey (AHS) for household and housing data.

The U.S. Census Bureau conducts national surveys every one decade. The 5-percent PUMS 2000 used in this study contains individual records of the characteristics for a 5 percent sample of people and housing units. The PUMS provides similar household and housing information as the RECS, but for the purpose of this study, it differs the RECS from two perspectives. First, county of residence in the PUMS could be identified, although for the reason of confidentiality the PUMS does not identify small counties in individual records with less than 100,000 population (Census 2004). The final samples used in this study include 266 metropolitan counties with 2,519,726 households. Second, the PUMS does not provide information on house size in square footage. Therefore, this study used the data from the PUMS to examine the relationship between urban sprawl and house type, while relied on the data from the AHS to explore the relationship between urban sprawl and house size.

The U.S. Census Bureau's American Housing Survey (AHS) collects more detailed information on the characteristics of housing units such as house size in square footage. The AHS includes a national survey and a metropolitan area survey with metropolitan areas and counties as the smallest geographic units, respectively. The national survey gathers information on housing throughout the country and interviews at about 55,000 housing units every 2 years, in odd-numbered years. The metropolitan area survey consists of 47 metropolitan areas, where householders are interviewed every 6 years. Data for about 14 metropolitan areas is gathered on an

even numbered year until all 47 metropolitan areas are surveyed. The cycle begins again 6 years later. Every 4 years, six of the largest metropolitan areas are included with the national sample.

To get county-specific information, this study used the metropolitan area survey. To match 2000 county-level sprawl index data, 1998 and 2002 metro surveys were pooled and used in this study to increase the statistical power of the analyses. To be noted, for the reason of confidentiality, small counties with population less than 100,000 are also combined and inseparable in the AHS. The final samples used in this study include 59 metropolitan counties with 61,947 households.

Table 6 of the Appendix records the descriptive statistics for all household and housing variables used in this study from the RECS, the PUMS, and the AHS, respectively. The descriptive statistics indicates that U.S. housing markets are not homogenous. Because the three surveys cover different geography, housing characteristics including house size, type, and year built differ for the three surveys. The average house size from the AHS, for example, is about 1,700 square feet, while the average house size from the RECS is approximately 2,100 square feet.

3. 1. 3 Land-use Data

Ewing, Schmid et al. (2003)'s 2000 county sprawl indices were used in this study to measure the degree of sprawling within major U.S. metropolitan counties. For more details on how the sprawl indices are developed, see section 2.2.3. Only large counties with population more than 100,000 were included in the final samples of this study in order to match household and housing data from the PUMS and the AHS. The final samples used together with the data from the PUMS include 266 U.S.

metropolitan counties with a total number of households of 2,519,726. The most sprawling county of the samples is Geauga County in Ohio, with a sprawl index of 63; while the most compact county is New York County, with a value of 352. The final samples used together with the data from the AHS include 59 metro counties with the total households of 61,947. The most sprawling county of the samples is Carroll County in Maryland, with a sprawl index of 82; while the most compact county is San Francisco County, with a value of 209.

3. 1. 4 Other Data

Besides energy use, household, and housing data, the following data is used in this study, including the heating and cooling degree-days from the RECS 2001, the size of metropolitan population from the U.S. Census Bureau, and the index of metropolitan residential construction cost in the year of 2000 from (R. S. Means Company 2000).

3. 2 Methodology

In this study, an ordinary least squares (OLS) regression model with STATA software was used to examine the dependence of residential energy use on housing unit characteristics, whereas hierarchical (multi-level) nonlinear and linear models with HLM 6 (Hierarchical Linear and Nonlinear Modeling) software were used to link urban sprawl to house type and house size, respectively. This section first explains why hierarchical models rather than the OLS models, the most often used statistical approach in social science, can better serve the second purpose of this study

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to link urban sprawl to housing stock, and then describes the specifications for all three models used in this study on sprawl, housing, and residential energy use.

3. 2. 1 Ordinary Least Squares Models vs. Hierarchical Models

In examining urban sprawl and house type or house size, households and their housing units share characteristics of a given place and thus violate the independence assumption of OLS regression. Standard errors of regression coefficients associated with place characteristics based on OLS regression will consequently be underestimated. Moreover, OLS regression coefficient estimates will be inefficient. Hierarchical or multilevel modeling overcomes these limitations, accounting for the dependence among households residing in a given place and producing more accurate standard error estimates (Raudenbush and Byrk 2002). Within a hierarchical model, each level in the data structure is represented by its own sub-model. Each sub-model represents the structural relations occurring at that level and the residual variability at that level.

In some HLM models, only intercepts are modeled as having randomly varying residuals, which are often termed "random intercept" models. In other HLM models, both intercept and coefficients are modeled as having randomly varying residuals, which are often termed "random coefficient" models.

3. 2. 2 Model Specifications

Housing and Energy Use Model

The OLS robust regression model was used to examine the impacts of housing unit characteristics on household energy use. The specification of the statistical

model for the total primary residential energy use per household per year is listed below:

$$\ln(\text{total energy demand}) = \propto + \text{B1} \ln(\text{House Size}) + \text{B2 House Type} + \text{B3 House Built Year} + \text{B4 Household Income} + \text{B5 Householder Race} + \text{B6 Number of Household Adults} + \text{B7 Number of Household Children} + \text{B8} \ln(\text{Energy Price}) + \text{B9 HDD} + \text{B10 CDD} + \text{Other Controls} + \mu$$

The dependent variable or outcome variable refers to the total primary residential energy use per household per year, including the use of natural gas, electricity, fuel oil, kerosene, and LPG. It is specified in the natural log format to satisfy the assumption of normality in OLS regression techniques. The output coefficients on the independent variables, therefore, represent the percent change in energy demand associated with a unit change in that independent variable.

The house size and house type variables, the mediators to link sprawl to residential energy use, are the interests of this study. The output coefficient on house size variable, which itself is expressed in the natural log format, represents the percent change in energy demand associated with each one percent change in square foot of house size. The house type variable refers to such dummies as single-family detached, single-family attached and multi-family housing with single-family detached housing as the reference group.

The house built year variable refers to such dummies as homes built before 1940, built between 1940 and 1959, built between 1960 and 1979, and built after 1980 with homes built before 1940 as the reference group. The householder race

variable refers to such dummies as white, black, Asia, Hispanic, and others with white householders as the reference group. The number of household adults or household children variable, respectively, represents the total numbers of household members sixteen years older or younger. The output coefficient on price of energy variable, which itself is expressed in the natural log format, represents the percent change in energy demand associated with each one percent change in the price of energy (i.e. price elasticity of energy demand). The output coefficients on HDD and CDD variables indicate percent changes, respectively, in energy demand associated with each one degree-day change in heating and cooling degree-days. Other controls include the square term of heating and cooling-degree days and the square term of the number of household adults and household children.

To be noted, some independent variables in the house and energy model are correlated to each other such as household income and house size. However, White test suggested that multicollinearity is not an issue for the model. The modeling result is reported in Table 7 of the Appendix, and the interpretation of the result is in the section 3.3.2.

In addition, all regression results reported in this dissertation were tested for multicollnearity, heteroscedasity, and non-linearity. All models in this dissertation were also weighted to account for different probabilities of sample selection and survey response.

Sprawl and House Type Model

A hierarchical nonlinear model was estimated for the trichotomous outcome, house type. Previous studies have shown that households' housing consumption is

dependent on household characteristics such as household income, the number of

household members, and ethic background (Skaburskis 1997; Miron 2004) and also

constrained by housing market conditions in the area such as the availability of

residential lands, residential construction cost, and other metro-specific characteristics

(Cheshire and Sheppard 1998; Wassmer and Baass 2005). In this study, the

trichotomous outcome, house type, was regressed not only on household

characteristics but on place-specific characteristics, including the county sprawl

index, residential construction cost index (R. S. Means Company 2000), and the size

of metropolitan population. The detailed model was described below:

At the household level:

$$Ln\_(P_{1ij}/P_{3ij}) = \beta_{0(1)j} + \sum_{q=1}^{Q} \beta_{q(1)j} X_{q(1)ij} + r_{(1)ij}$$

$$Ln\_(P_{2ij}/P_{3ij}) = \beta_{0(2)j} + \sum_{q=1}^{Q} \beta_{q(2)j} X_{q(2)ij} + r_{(2)ij}$$

At the county level:

$$\beta_{q(1)j} = \mu_{q(1)0} + \sum_{s=1}^{S} \mu_{q(1)s} W_{s(1)j} + \omega_{q(1)j}$$

$$\beta_{q(2)j} = \mu_{q(2)0} + \sum_{s=1}^{S} \mu_{q(2)s} W_{s(2)j} + \omega_{q(2)j}$$

There are i = 1, …, n_j level-1 households nested within j = 1, …, J level-2

counties.

Where

$Ln\_(P_{1ij} / P_{3ij})$ and $Ln\_(P_{2ij} / P_{3ij})$ respectively represent the natural log of

odds of household i in county j living in single-family attached and multifamily

housing rather than single-family detached housing;

$\beta_{q(1)}$ and $\beta_{q(2)}$ (q = 0, 1, …, Q) are household-level coefficients;

$X_{q(1)}$ and $X_{q(2)}$ are household-level predictor q, including housing unit

characteristics such as the built year and household characteristics such as annual

household income, the number of household members, race of householder, etc.;

$r_{(1)}$ and $r_{(2)}$ are household-level random effects;

$\mu_{sq(1)}$ and $\mu_{sq(2)}$ (q = 0, 1, …, Q) are county-level coefficients;

$W_{sq(1)}$ and $W_{sq(2)}$ are county-level predictor s, including the degree of sprawl

within counties, the residential construction cost index and total population of the

metro area;

$\omega_{q(1)}$ and $\omega_{q(2)}$ are the county-level random effects.

This study initially allowed only the intercept terms $\beta_{0(1)}$ and $\beta_{0(1)}$ to vary as

functions of place characteristics plus randomly varying residuals, referred to as

"random intercept" models. Then this assumption was relaxed and coefficients were

also modeled as functions of place characteristics plus randomly varying residuals,

effectively permitting interactions between place and household characteristics,

referred to as "random coefficient" models. The random intercept and random

coefficient models are respectively reported in Table 8 and 9 of the Appendix, and the

interpretations of the results are respectively in the sections 3.4.2 and 3.5.2.

Sprawl and House Size Model

A hierarchical linear model was estimated for the continuous outcome, house size. The relationship between sprawl and households' demand for house size was estimated with the following linked statistical models:

$$Y_{ij} = \beta_{0j} + \sum_{q=1}^{Q} \beta_{qj} X_{qij} + r_{ij}$$

$$\beta_{qj} = \gamma_{q0} + \sum_{s=1}^{S} \gamma_{qs} W_{sj} + u_{qj}$$

Where

Y_{ij} is the outcome variable, representing household$_i$'s house size living in county j;

β_q, X_q, r, γ_{qs} W_s, and μ_q are noted the same as those in sprawl and house type model, expect that X_q here also include house type which is the dependent variable in sprawl and house type model.

This study also initially allowed only the intercept term β_0 to vary with place characteristics plus a random effect. Then this assumption was relaxed and coefficients were also modeled as functions of place characteristics plus randomly varying residuals. The interactions between place and household characteristics were seldom significant and never sufficiently large to appreciably affect the relationships between county characteristics and outcome variable, house size. Hence, only the result from the random intercept model is reported in Table 10 of the Appendix.

3. 3 Impact of Housing on Residential Energy Use

3. 3. 1 Descriptive Analysis Results

The average U.S. home has been getting larger. According to the RECS 2001, in the year of 2001, the median and mean floor area of existing homes is about 1,750 and 2,050 square feet, respectively. Around 20 percent of existing housing units are larger than 3,000 square feet. Single-family detached housing is the dominant U.S. house type, accounting for about two-thirds of the total housing units. More than half of the housing units are built after 1960.

In the year of 2001, an average U.S. household consumes around 137,000 thousand Btu of primary energy, or 95, 000 thousand Btu of delivered energy, to heat, cool, light their homes and operate their home appliances and equipment. The total primary energy use per household per year significantly differs across house type, house size, and the house built year.

An average U.S. household, for example, living in single-family detached housing, consumes almost double the primary energy than a household living in multifamily housing. Although the mean floor area of existing mobile homes is 990 square feet, 80 square feet less than the mean floor area of existing multifamily housing, an average mobile home is far less energy efficient than an average multifamily housing unit and consumes 35 percent more primary energy (for more details, see Figure 11).

Figure 11: Total Annual Primary Household Energy Use by House Type, 2001 (Source: 2001 RECS)
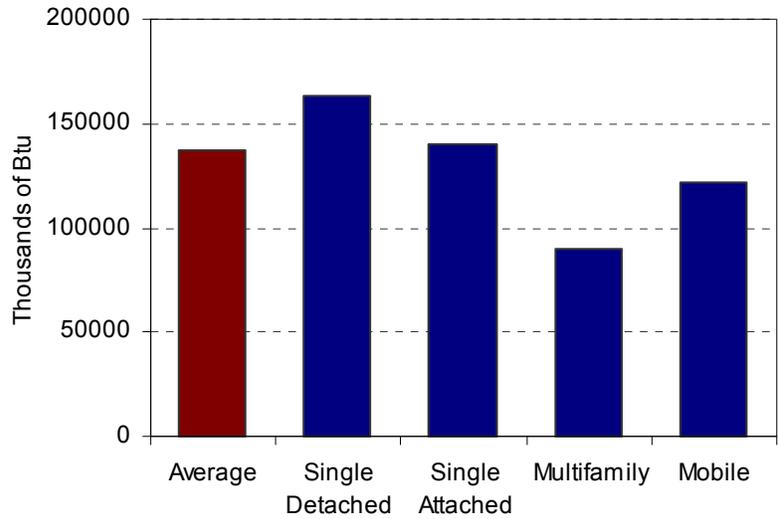
Large houses consume more energy than small houses. A house with floor area between 2000 to 3000 square feet, for example, consumes almost double of primary energy than a house less than 1000 square feet (see Figure 12).

Figure 12: Total Annual Primary Household Energy Use by House Size in Square Footage, 2001 (Source: 2001 RECS)
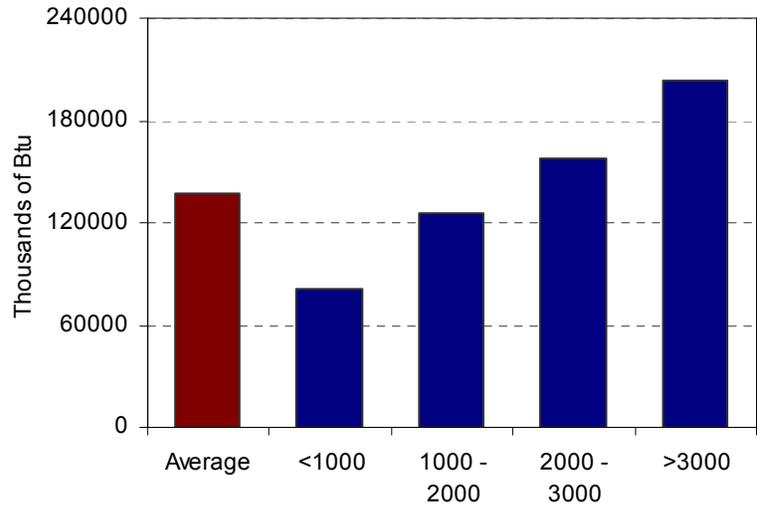
Newly built houses are more energy efficient than old ones because of better insulation. A house built before 1940, for example, consumes 35 percent more of primary energy than a house built between 1960 and 1979 (see Figure 13).

Figure 13: Total Annual Primary Household Energy Use by Year Built, 2001 (Source: 2001 RECS)
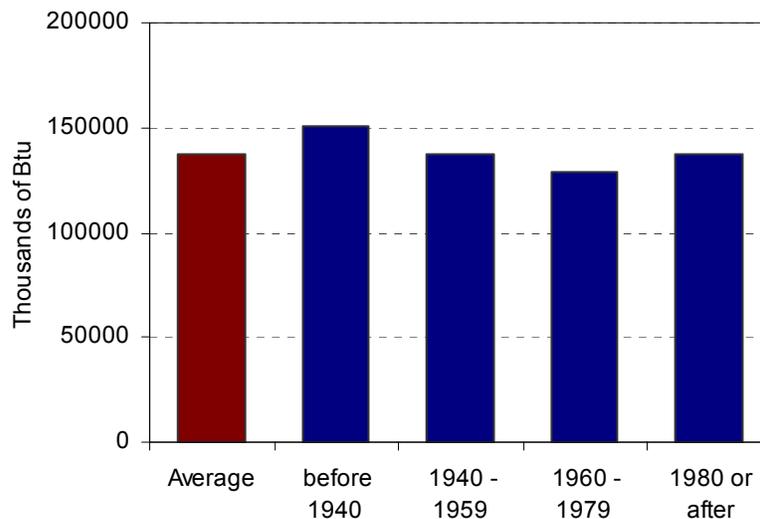
3. 3. 2 Ordinary Least Squares Model Results

As expected, the primary energy consumed annually at home is strongly dependent on climate. Regression results for housing and energy use model confirm a positive relationship between household energy use and total numbers of heating and cooling degree-days (see Table 7 of the Appendix for regression coefficients, t-ratios, and significance levels).

Energy use decreases with energy price. The elasticity of total primary energy use per household per year with respect to energy price (dollar per thousand Btu) is -0.34. Each ten-percent change in the price of energy is associated with a four-percent

change in energy demand. Energy use increases with the number of household members and with annual household income, and varies by race/ethnicity. For example, otherwise comparable households with annual household income $75,000 or more consume 17 percent more primary energy than households with annual household income $30,000 or less. Otherwise comparable black households consume 9 percent more primary energy than white households, while Hispanic and Asian households consume 17 and 21 percent less than white households. This might be caused by different attitudes regarding energy conservation and different household preferences for energy efficient equipment and appliances, the factors not modeled in this study due to data limitations but perhaps partially captured with race/ethnicity variables.

Controlling for these covariates, the total amount of primary energy use per household per year is strongly related to the physical characteristics of housing units. Because of better insulation of walls, windows, roofs, etc. newly built houses are more energy efficient than old ones. Thanks to exposing much lees roof, walls and windows to the sun, rain and winds, both multifamily and single-family attached housing are more energy efficient than single-family detached housing. The regression results show that otherwise comparable households living in single-family detached housing consume 22 percent more primary energy than those living in multifamily housing and 9 percent more than those living in single-family attached housing.

Larger houses use more energy for heating, cooling, or lighting. The elasticity of energy use with respect to floor area is 0.25. A household living in a 2000-square-

feet house is expected to consume 25 percent more primary energy than a household living in a 1000-square-feet house.

3. 4 Impact of Sprawl on House Type

3. 4. 1 Descriptive Analysis Results

The housing mix, shares of single-family detached, single-family attached and multifamily housing, differs across U.S. metropolitan counties. Among the 448 counties covered by the sprawl and house type model, the highest share of multifamily housing is 99.2 percent in New York County, with a sprawl index of 352, while the lowest share is 0.6 percent in New Kent County, Virginia, with a sprawl index of 73. Figure 14 and 15 plot the shares of single-family detached and multifamily housing in the 448 counties versus the corresponding sprawl index. Both figures provide gross evidence of a relationship between the housing mix and the degree of urban sprawl.

Figure 14: Shares of Single-Family Detached Housing vs. County Sprawl Index, 2000
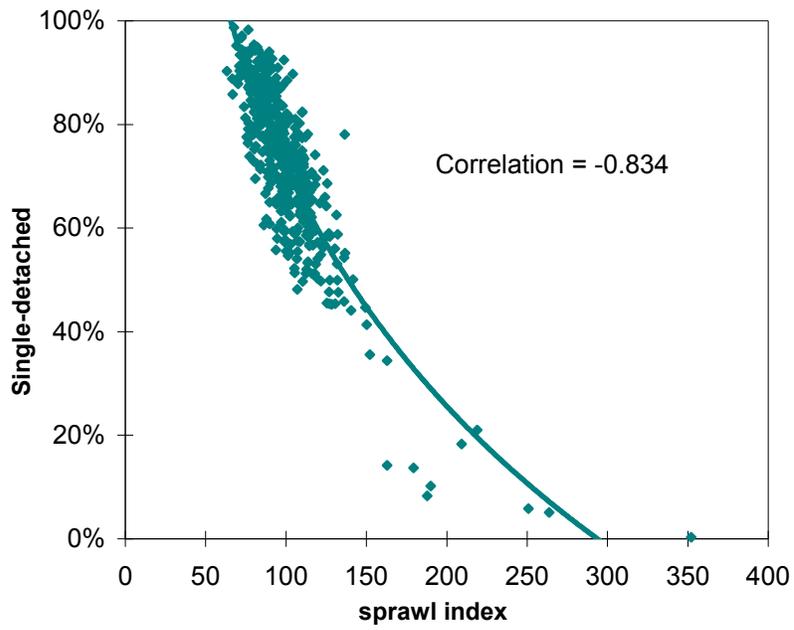
Figure 15: Shares of Multifamily Housing vs. County Sprawl Index, 2000
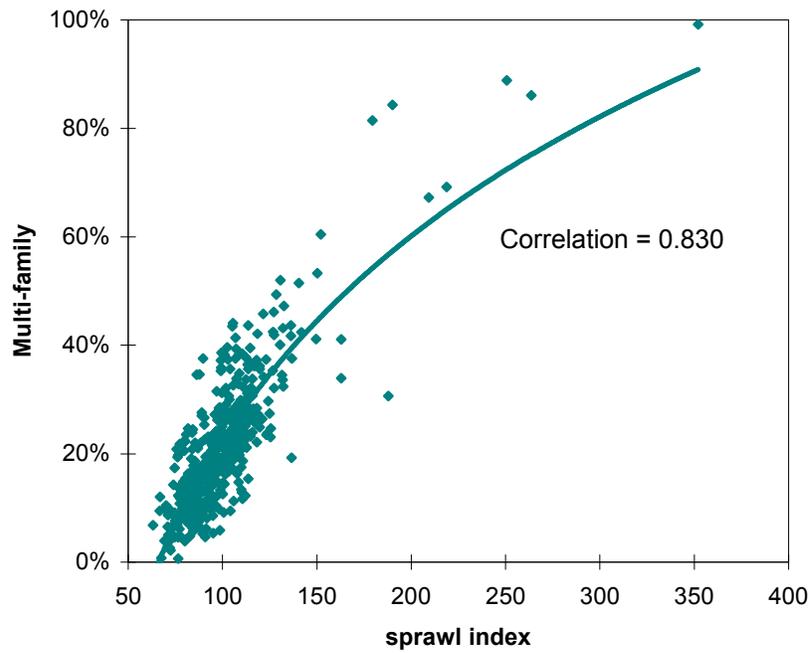
3. 4. 2 Hierarchical Model Results

Hierarchical nonlinear modeling and disaggregate data were used to quantify the relationship between urban sprawl and house type, controlling for household income and other confounding influences. Table 8 and 9 of the Appendix report regression results for random intercept and random coefficient models.

As expected, household preferences for different house types are strongly related to household characteristics. All else being equal, the likelihood of a household living in a single-family attached or multifamily home decreases with the number of household members and with annual household income. It is greater for black, Hispanic, or Asian households than white households.

Residential construction cost and metropolitan area size were also controlled for in this study. Residents of metropolitan areas with higher residential construction costs are more likely to live in multifamily or single-family attached housing. No statistically significant result was found for metropolitan area size, measured by population.

Controlling for these covariates, the county sprawl index is strongly related to households' choices of house types. For both random intercept and random coefficient models, residents of compact counties are more likely to live in multifamily or single-family attached housing than are residents of sprawling counties. From the random intercept model, for example, the odds of households living in multifamily or single family attached rather than single-family detached housing are respectively 7 and 5 times higher for compact counties, one standard

deviation above the mean sprawl index, than for sprawling counties, one standard deviation below the mean index (that is, for a 50-point spread).

The random coefficient model captures the interaction of variables at different levels, thereby allowing us to compare the effects of sprawl on households with different socioeconomic characteristics. Sprawl has a stronger relationship to housing choice for white households than other races/ethnicities and for high-income households than low-income households. For example, the odds of white households living in multifamily housing are 4 times higher for compact counties, one standard deviation above the mean sprawl index, than for sprawling counties, one standard deviation below the mean index (a 50-point spread), while the odds of Hispanic households living in multifamily housing are only 2 times higher.

3. 5 Impact of Sprawl on House Size

3. 5. 1 Descriptive Analysis Results

Median house size also differs across U.S. metropolitan counties. Among the 59 counties covered by the sprawl and house size model, the smallest median house size is about 1000 square feet in the San Francisco County, with a sprawl index of 209, and the largest median house size is approximately 2300 square feet in the Waukesha County, Wisconsin, with a sprawl index of 90. Figure 16 provides gross evidence of a positive relationship between median house size and the degree of sprawl in metro counties.

Figure 16: County Median House size vs. County Sprawl Index, 2000
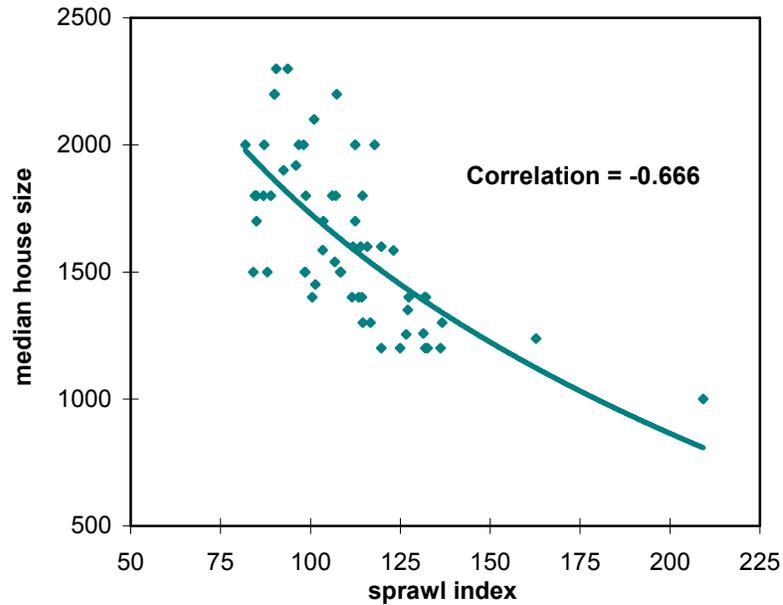
3. 5. 2 Hierarchical Model Results

Hierarchical linear modeling and disaggregate data were used to quantify the relationship between urban sprawl and house size, controlling for household income and other confounding influences. Table 10 of the Appendix reports regression results for the random intercept model.

As expected, households' demand for floor areas is strongly related to household characteristics. All else being equal, house size in square foot increases with the number of household members and with annual household income. House size is larger for white households than black, Hispanic, or Asian households. House size is also related to house type and built year. Single-family detached houses are larger than single-family attached or multifamily houses. Newly built houses are larger than those built earlier.

Residential construction cost and metropolitan area size were also controlled in this study. No statistically significant result was found for either variable.

Controlling for all these covariates, the county sprawl index is strongly related to house size. Residents of sprawling counties are expected to live in larger houses than residents of compact counties. All else being equal, for example, houses are 19 percent larger in sprawling counties, one standard deviation below the mean sprawl index, than in compact counties, one standard deviation above the mean index.

3. 6 Synthesis

After controlling for household characteristics, the physical characteristics of housing units are found to have a strong relationship to residential energy use. Residents of single-family detached housing, for example, are expected to consume 22 percent more primary energy than those of multifamily housing and 9 percent more than those of single-family attached housing. Larger houses use more energy than smaller ones. The elasticity of energy use with respect to floor area is 0.38. A household living in a 2000-square-feet house is expected to consume 38 percent more primary energy than a household living in a 1000-square-feet house.

After controlling for household and place covariates, the county sprawl index is also found to have a strong relationship to housing unit characteristics. The odds of households living in multifamily or single family attached rather than single-family detached housing are respectively 7 and 5 times higher for compact counties, one standard deviation above the mean sprawl index, than for sprawling counties, one standard deviation below the mean index (that is, for a 50-point spread). Meanwhile,

otherwise comparable households in compact counties, one standard deviation above the mean sprawl index, have 19 percent less floor area than in sprawling counties, one standard deviation below the mean index.

These relationships above, taken together, allow us to relate residential energy use to urban sprawl, indirectly through the mediators of house type and house size. Due to a higher likelihood of living in multifamily housing and of living in relatively smaller houses, an average white household (with two adults and two children, with annual household income between $50,000 to $75,000, and living in a house built in between 1940 and 1959), would be expected to consume about 13 percent less primary energy living in a compact county, one standard deviation above the mean sprawl index, than in a sprawling county, one standard deviation below the mean index,. In the year of 2001, an average U.S. household consumed about 137,300 thousands of Btu of primary energy, or spent energy expenditures of $1,500, to heat, cooling, light their homes and operate their home equipment and appliances. The 13-percent annual difference on primary energy use is equal to 17,900 thousands of Btu of primary energy, or energy expenditures of more than $200, between residents of compact counties and sprawling counties.

The indirect impact of sprawl on residential energy use through the house effect including house type and size is as comparably significant as the impact of sprawl on transportation energy use. A study on the impact of sprawl on transportation energy use suggests that the average Atlanta household is expected to drive 25 percent fewer miles if it relocates to relatively compact Boston (Bento, Cropper et. al. 2003). If we assume total vehicle driven miles of 12,000 per year, fuel

economy of 22 miles per gallon, and a price of $2.5 per gallon gasoline, this study

suggests that the average Atlanta household would spend around $340 less on annual

driving cost if it relocates to relatively compact Boston. While this dissertation

discloses that the average Atlanta household would spend about $250 less on annual

household energy bills if it lives in relatively compact Boston, purely due to the

housing effect from sprawl.

Chapter 4: Study on Sprawl, UHI, Residential Energy Use

4. 1 Data

The objective of this study is to first explore whether or not nationwide urban cities experience higher temperatures than their surrounding rural areas, then examine the impact of the urban heat island effects on residential energy use for space heating and cooling, and last explore the impact of urban sprawl on the formation and intensity of heat islands. To achieve the first goal, we compared the differences between the observed surface temperatures and the corresponding NNR-derived values. Both data are dedicated to the research work of Kalnay and Cai (2003). To achieve the second goal, we need the data on space-conditioning energy use and the data on the characteristics of households and housing units. The Energy Information Administration (EIA)'s Residential Energy Consumption Survey (RECS) alone could well serve this purpose (EIA 2004b). To achieve the third goal, we need county-specific data on urban heat island intensities, the degree of sprawling, size of population, and topographic features such as plain, valley, and coast. Ewing, Brownson et al. (2006)'s 2000 county sprawl indices were used in this study to measure the degree of sprawling within major U.S. metropolitan counties. Such county-specific data as size of population, size of area and other geographic spatial data are from ESRI's Data & Maps 2005 (ESRI 2005).

4. 1. 1 Temperature Data

Two different temperature data sources were used in this study for two different purposes. One is annual heating and cooling degree-day data in 2001 from the RECS 2001, which is used to examine the dependence of space-conditioning energy use on heating and cooling degree-days. The other is temperature data taken from the research work of Kalnay and Cai (2003), which is used to quantify the urban heat island intensity in metropolitan counties.

The values of heating and cooling degree-days in the RECS 2001 were based upon data obtained from National Oceanic & Atmospheric Administration (NOAA). They are annual degree-days, which are calculated by summing the daily degree-days and use the base temperature of 65 °F. A random error was then added to both degree-day data to mask the location of the weather station from which the data was obtained (EIA, 2004b). For the details on how to calculate degree-day data, please see the section 4.2.1.

The temperature data taken from the research work of Kalnay and Cai (2003) include both the observed surface temperatures from weather stations and the corresponding interpolated data from gridded NCEP-NCAR 50-year Reanalysis (NNR). For the surface observations, Kalnay and Cai (2003) used the daily maximum and minimum surface station temperatures from the National Climate Data Center (NCDC) "Cooperative Summary of the Day" data set over the forty-eight contiguous states of the United States from 1950–1999. They then derived the monthly average surface temperatures and interpolated linearly the corresponding NNR data to each observational site. They only considered the sites that have a total

of at least 480 (whole) months of observations. In addition, because the NNR has

surface heights different from those of the real locations and extrapolations

underground can introduce errors overwhelming the signal of the real trends, in the

computation of the trends they only considered sites with elevations lower than 500

meters. There are 1,982 U.S. surface stations satisfying these two conditions with

both the observed surface temperature data and the corresponding NNR data. These

stations are located over 1,484 U. S. metro or non-metro counties. For more details

about the data source, please refer to the work of Kalnay and Cai (2003).

4. 1. 2 Energy Data

Energy data is also from the EIA's RECS 2001.   The RECS not only provides

energy use data, household and housing characteristics data (for more details, see the

section 3.1.1), but detailed information on how U.S. households heat or cool their

homes, which is critical to the purpose of this study. The information that the RECS

provided includes the main fuel used for heating or cooling homes (natural gas,

electricity, fuel oil, LPG, kerosene, wood, etc.), type and the age of heating or cooling

equipment providing the services, and if the thermostats of this equipment are

programmable.

Although the RECS 2001 has limited sample size and does not have the

necessary data coverage to make statistically valid state-level analyses for the entire

United States, it does provide detailed summaries of the four largest States including

New York, California, Texas, and Florida.   These not only allow this study to

estimate nationwide average energy demand response to the changes in heating and

cooling degree-days, but to compare if the energy demand response is different in States with a cold climate and in States with a hot climate.

Among the total sample of 4, 852 households in the RECS 2001, 4,666 households heat their homes and 3,406 households cool their homes, which are respectively, included in the heating and cooling energy use models described in the section 4.2.3

4. 1. 3 Land-use Data

Ewing, Brownson et al. (2006)'s 2000 expanded county sprawl indices were used in this study to measure the degree of sprawling within U.S. metropolitan counties. Their county sprawl indices cover 938 U.S. metropolitan counties or county equivalents (e.g. independent cities). About 83 percent of U.S. population lived in the 938 counties in 2000. For more details on how the sprawl indices were developed, please see the section 2.2.3.

Among the total sample of 938 metropolitan counties, there are 543 counties with both the observed surface temperatures and the corresponding NNR-derived data, which allow us to obtain urban heat island intensities for these counties. The 543 metro counties, therefore, are included in the final sample of the model linking sprawl to the urban heat island intensity. These counties are mostly lying within non-mountainous regions from the forty-three contiguous states of the United States.

4. 1. 4 Geographic Spatial Data

All the geographic spatial data is from ESRI Data & Maps 2005 (ESRI 2005). The ESRI Data and Maps 2005 contains many types of map data at many scales of

geography. For each geography included, the significant basemap layers are boundaries, cities, rivers, and roads. This generalized basemap information is available for the World, Canada, Mexico, the United States, and Europe. In addition, where possible, demographic data is provided for sub-national boundaries such as states, counties, or their equivalents. This study used ESRI Data & Maps 2005's U.S. County Boundary file to locate and present the temperature data from the work of Kalnay and Cai (2003) and conduct necessary spatial analyses, as well as the data source for such county-specific characteristics as size of population, size of area, etc. There are in some counties two or more weather stations with slightly different temperatures. In this case, the ESRI Data & Maps 2005's U.S. Census Tract file was used to calculate the population-based temperatures by Census Tract.

Such county-specific topographic features as coast, plain, and valley were derived from the ESRI Data & Maps 2005's North America Digital Elevation Model. It represents an elevation map for North America, which is derived from the global digital elevation model (DEM) - GTOPO30 data sets from the U.S. Geological Survey's EROS Data Center Distributed Active Archive Center (EDC DAAC). The value attribute represents the elevation in meters (for the map, see Figure 17). In this study, counties with coast as their topographic features refer to the ones located by the sea; counties with plain as their topographic features refer to the ones with more than 75 percent of areas located less than 250 meters above the sea level; and counties with valley as their topographic features refer to the ones with more than 75 percent of areas located more than 250 meters above the sea level.

Figure 17: North America Digital Elevation (Source: ESRI Data & Maps, 2005)
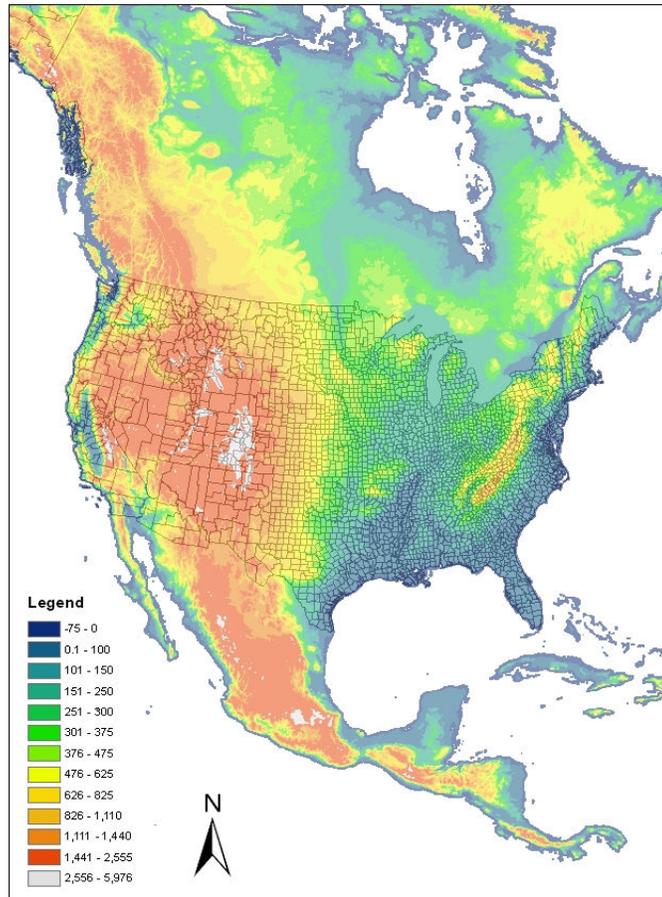
4. 2 Methodology

The interest of this study is the space-conditioning energy use. The degree-day approach is often used as a common energy accounting practice for estimating this temperature-sensitive energy (Sailor and Munoz 1997; Amato, Ruth et al. 2005). This section first introduced what a degree-day approach is and how degree-days are derived from temperatures, then explained the methodologies used to quantify the UHI intensities, and concluded with the statistical approaches to link degree-days to

space-conditioning energy use and the statistical approaches to link urban sprawl to the UHI intensities, as well as the specifications for all related models used in this study.

4. 2. 1 Degree-day Formulation

Degree-days are a common energy accounting practice for estimating energy demand in which energy demand is broken down into three components (Jager 1983): (1) non-temperature-sensitive energy, (2) heating energy, and (3) cooling energy. The degree-day approach presumes a V-shaped energy demand-temperature relationship (see Figure 18). If outdoor temperature is lower than the balance point temperature then energy is required for heating services, whereas if outdoor temperature is higher than the balance point temperature then energy is required for cooling services.

Figure 18: Theoretical Relationship between Temperature and Energy Demand (Source: Jager 1983)
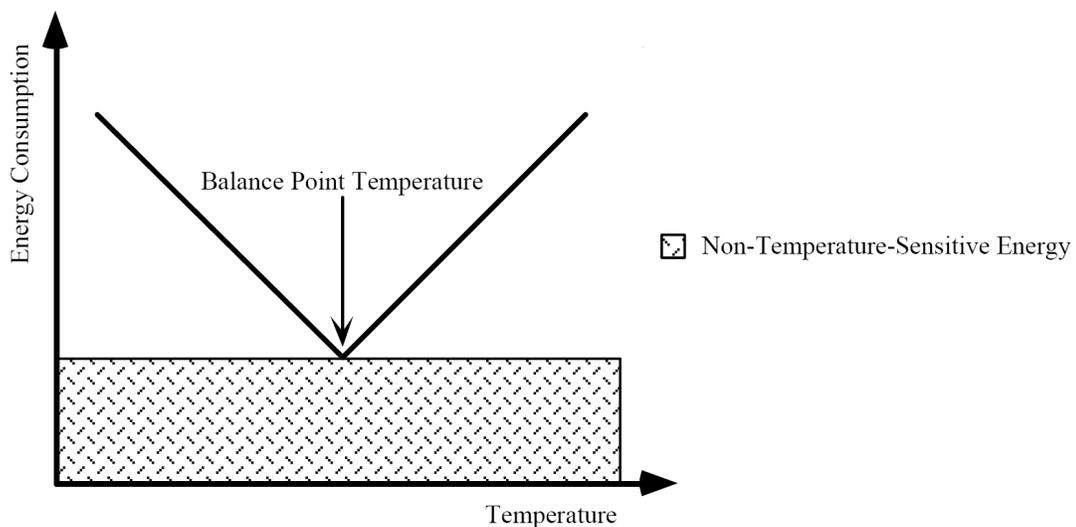
To reflect the heating and cooling components of space-conditioning energy, degree-days are comprised of heating degree-days (HDDs) and cooling degree-days (CDDs). Heating degree-days can be thought of as an index of "coldness," whereas cooling degree-days as an index of "hotness." Coldness and hotness are temperature differences from "just rightness" – as defined by the balance point temperature. In other words, heating degree-days and cooling degree-days are measures of the combined intensity and duration of coldness and hotness, respectively, over a specified time period.

Each degree deviation from the balance point temperature is counted as a degree-day. For example, if the balance point temperature is 65 °F and the day's mean temperature is 50 °F, this results in 15 heating degree-days for that day. If the balance point temperature is 65 °F and the day's mean temperature is 80 °F, this results in 15 cooling degree-days for that day. Degree-days can be accumulated over time to give weekly, monthly or annual totals. In this study, the balance point temperature is 65 °F and degree-days are annual totals.

To be noted, it is not the case that a degree day calculation will capture each and every need for heating or cooling services. First, there is the possibility of extreme high and low temperatures which can be obscured by daily averages (K. Baumert and M. Selman, 2003). Second, other climatic factors, such as humidity and wind, will also influence the demand for heating and cooling services (Sailor, 1998). Last, the balance point temperature is found to be different for heating and cooling and also different by region (Amato, A., M. Ruth, et al. 2005). They are, for example, generally higher in south, reflecting both somewhat higher thermostat

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settings and lower insulation levels of the building stock (Belzer DB, and KA Cort 2004). Overall, degree days should be understood as a reasonable approximation rather than exact measure of the heating and cooling needs of a particular city, region, or country.

4. 2. 2 Methods Quantifying UHI Intensities

As described in the section 2.3.2, there are two major methodologies to quantify UHI intensities. The traditional methodology is to compare observations in cities with those in surrounding rural areas. The other is to compare the difference between the observed surface temperatures and the corresponding NNR values (Kalnay and Cai 2003). More information about the NNR-derived values can be found in the section 2.3.2.

Compared to the first one, the advantage of the second methodology is its feasibility to derive nationwide UHI intensities, because there is no need to classify urban and rural areas or worry about whether climate readings from a rural station can be used as readings of synoptic weather. The disadvantage of the second methodology, however, is that it cannot be used in mountainous regions, where the correlation between the observed surface temperatures and the corresponding NNR values is not strong enough to derive reliable estimates (Kalnay and Cai 2003). After measuring the pros and cons of the two methodologies, this study adopted the second one to measure UHI intensities, because it is the only method found yet that could be used to derive nationwide UHI intensities.

To remove the noises from years with unusual climate, this study compared the long-term average differences between the observed values and the corresponding

NNR data from 1970–1999, including the differences in monthly average minimum, maximum, and mean temperatures and the differences in heating and cooling degree-days.   The degree-day data used here is derived from monthly average temperatures because (1) the NNR-derived values are monthly average temperatures; (2) there are studies in which monthly average temperatures are used to derive degree-day data because of the lack of consistent long-term daily average temperatures. The specifications of all measures used are listed below:

$$\text{UHI Intensities}\_ {\text{Maximum Temperatures}}$$
$$= \text{Observed}\_ {\text{Maximum Temperatures}} - \text{NNR}\_ {\text{Maximum Temperatures}}$$

$$\text{UHI Intensities}\_ {\text{Minimum Temperatures}}$$
$$= \text{Observed}\_ {\text{Minimum Temperatures}} - \text{NNR}\_ {\text{Minimum Temperatures}}$$

$$\text{UHI Intensities}\_ {\text{Mean Temperatures}}$$
$$= \text{Observed}\_ {\text{Mean Temperatures}} - \text{NNR}\_ {\text{Mean Temperatures}}$$

$$\text{UHI Intensities}\_ {\text{HDDs}}$$
$$= \text{Observed}\_ {\text{HDDs}} - \text{NNR}\_ {\text{HDDs}}$$

$$\text{UHI Intensities}\_ {\text{CDDs}}$$
$$= \text{Observed}\_ {\text{CDDs}} - \text{NNR}\_ {\text{CDDs}}$$

4. 2. 3 Statistical Approaches to Link Degree-Day to Energy Use

The OLS robust regression models with STATA software were used to examine the dependences of the total primary residential energy use for space heating and cooling on heating and cooling degree-days, respectively. The specifications of the statistical models for space heating and cooling energy use are listed below:

Heating Degree-day and Energy Use Model:

ln(heating energy demand) = $\propto$ + B1 HDD+ B2 House Size + B3 House Type + B4 House Built Year + B5 Household Income + B6 Householder Race + B7 ln(Price) + Other Controls + μ

Cooling Degree-day and Energy Use Model:

ln(cooling energy demand) = $\propto$ + B1 CDD+ B2 House Size + B3 House Type + B4 House Built Year + B5 Household Income + B6 Householder Race + B7 ln(Price) + Other Controls + μ

The dependent variable in each energy model is specified in the natural log format. The output coefficients on the independent variables, therefore, represent the percent change in energy demand associated with a unit change in that independent variable. The output coefficients on HDD and CDD variables, the interests of this study, indicate the percent changes, respectively, in heating and cooling energy demand associated with each one degree-day change in heating and cooling degree-days.

The output coefficient on house size variable indicates the percent change in energy demand associated with each one square foot change in house size. The house type variable refers to such dummies as single-family detached, single-family attached, multi-family, and mobile housing with single-family detached as the reference group. The house built year variable refers to such dummies as home built before 1940, built between 1940 and 1959, built between 1960 and 1979, and built after 1980 as home built before 1940 as the reference group. The householder race

variable refers to such dummies as white, black, Asia, Hispanic, and others with white householders as the reference group. The output coefficient on price of energy variable, which itself is expressed in the natural log format, represents the percent change in energy demand associated with each percent change in the price of energy (i.e. price elasticity of energy demand). Other controls include the age of heating or cooling equipment variable (dummies as less or more than 10 years old), the programmability of the thermostat of heating or cooling equipment variable (dummies as yes or no), the building insulation variable (dummies as well or poorly insulated), if the cooling equipment are central or not (dummies as yes or no), and if there is someone at home all day on a typical weekday (dummies as yes or no).

In addition to the statistical models described above, the statistical models for the heating and cooling energy use are separately developed for each of the four largest States including New York, California, Texas, and Florida, where data is available. By analyzing each State independently, demand responses may be observed for an individual State that may have been obscured at a more aggregate level. For example, each one degree-day increase in cooling degree-days may have larger marginal affects on cooling energy demand in States with a hot climate than States with a cold climate, while each one degree-day increase in heating degree-days may have larger marginal affects on heating energy demand in States with a cold climate than States with a hot climate. The modeling results for both the national model and the State models were reported in Table 11 and 12 of the Appendix, respectively.

4. 2. 4 Statistical Approaches to Link Sprawl to UHI

Although since until now no study linking sprawl to heat island formation has been available, there are similar studies identifying the dependence of heat islands on some geographic factors. Statistical approaches, for example, have been proposed to evaluate the latitudinal dependence of heat islands (Wienert and Kuttler 2005). In Wiener and Kuttler's study, a multiple regression analysis with the daily maximum UHI as the dependent variable and size of city population, annual energy use (indicator for anthropogenic heat production), height above sea level, and topography feature (coast, plain, valley) as independent variables was performed. Their samples include 223 cities between latitudes 43° S and 65° N with a broader global data base and they found that the part of the observed variance of daily maximum UHI can be explained by the latitudinal variation.

This study used the similar approach to examine the dependence of heat islands on the degree of sprawling. The specifications of the statistical models controlling for the degree of sprawling are listed below:

Sprawl and UHI Model (Changes in HDDs):

$\ln$(UHI Intensity $_{\Delta \text{HDD}}$) = $\propto$ + B1 $\ln$(County Sprawl Index) + B2 $\ln$(Size of County Population) + B3 Latitude + B4 Longitude + B5 Topographic Feature + μ

Sprawl and UHI Model (Changes in CDDs):

$\ln$(UHI Intensity $_{\Delta \text{CDD}}$) = $\propto$ + B1 $\ln$(County Sprawl Index) + B2 $\ln$(Size of County Population) + B3 Latitude + B4 Longitude + B5 Topographic Feature + μ

The dependent variable in each model is the natural log of the heat island intensity measured by the changes in heating and cooling degree-days. The output coefficients on the independent variables, therefore, represent the percent change in UHI intensities associated with each unit change in that independent variable.

The county sprawl index variable, the interests of this study, covers such information as population density, block size, and potentially the intensity of anthropogenic heat production (Newman and Kenworthy 1996; Crane and Crepeau 1998; EPA 2001; Bento, Cropper et al. 2003; Biirer, Goldstein et al. 2004). The output coefficient on variable, which itself is expressed in the natural log format, represents the percent change in the UHI intensities associated with each percent change in the sprawl index.

The output coefficient on size of county population variable, which is also expressed in the natural log format, represents the percent change in the UHI intensities associated with each percent change in the size of county population. The latitude and longitude variables refer to the geographic location of the weather station located within the county. In the case that there are two or more weather stations in one county, the average latitude and longitude are used in this study. The output coefficients of these two variables, therefore, could measure the latitudinal and longitudinal dependences of heat island intensities, respectively. The topographic feature variable refers to such dummies as coast, plain, and valley with plain as the reference group. The modeling result was reported in Table 13 of the Appendix.

In addition, the statistical models for the changes in heating and cooling-degree days due to heat island formation are also developed by controlling for size of

county area rather than the county sprawl index. The purpose is to simply examine the dependence of heat island intensities on size of county population and area without considering the factor of urban design, which the sprawl index covers to some degree. The specifications of the two statistical models controlling for the size of county area are listed below:

$$\ln(\text{UHI Intensity}_{\_\Delta\text{HDD}}) = \propto + \text{B1} \ln(\text{Size of County Area}) + \text{B2} \ln(\text{Size of County Population}) + \text{B3 Latitude} + \text{B4 Longitude} + \text{B5 Topographic Feature} + \mu$$

$$\ln(\text{UHI Intensity}_{\_\Delta\text{CDD}}) = \propto + \text{B1} \ln(\text{Size of County Area}) + \text{B2} \ln(\text{Size of County Population}) + \text{B3 Latitude} + \text{B4 Longitude} + + \text{B5 Topographic Feature} + \mu$$

4. 3 Evidence of UHI Phenomena

4. 3. 1 Changes in Temperatures

This study compared the long-term average monthly maximum, minimum, and mean temperatures of 1,982 surface stations located below 500 meters over the 48 contiguous United States with the corresponding NNR values for the period 1970-1999. Because the NNR values should not be sensitive to urbanization or land-use effects, we could attribute the temperature differences between the observed and NNR values primarily to urbanization and other changes in land use.

The differences in monthly minimum temperatures between the observed and NNR values are strongly positive during all months of the year and the largest values are seen in the summer or warm half of the year. The difference in June, for example,

is as high as 4.3 °F, compared with a yearly average increase of 2.7 °F (for detailed

results, see Figure 19).

Figure 19: Long-Term Average Monthly Temperature Differences between the
Observed and the NNR Values (1970-1999)
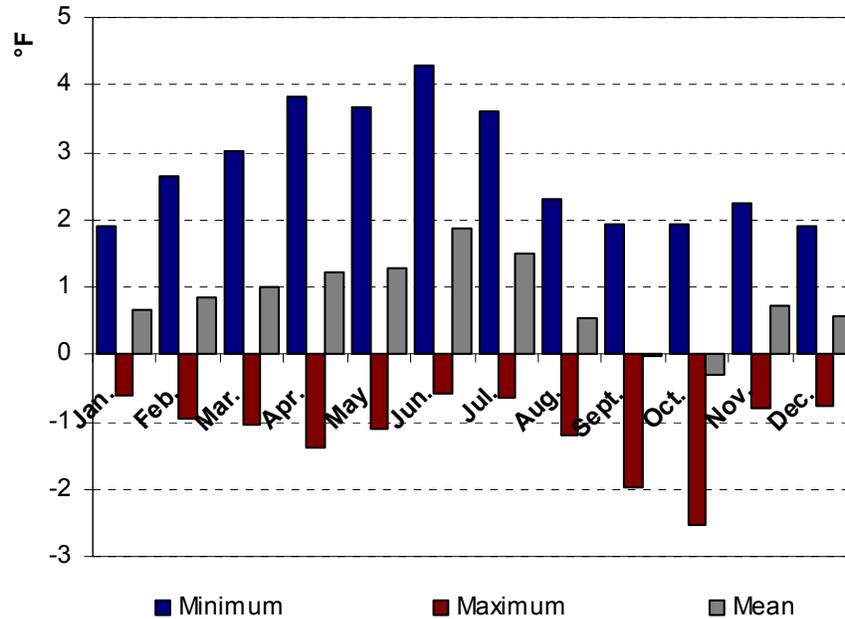
Nationwide, the differences in monthly minimum temperatures are mostly

positive, especially in the eastern and the western U.S. (see Figure 20). The results

here are compatible with the general conclusion on urban heat islands: the well-

known urban heat island effect actually takes place at night, when buildings and

streets release the solar heating absorbed, and the effect is usually stronger in the

summer or warm half of the year because the greater solar energy input and lower

wind speeds (Morris, Simmonds et al. 2001; Voogt 2004).

Figure 20: Long-Term Average Monthly Minimum Temperature Differences between the Observed and NNR values (1970 - 1999)
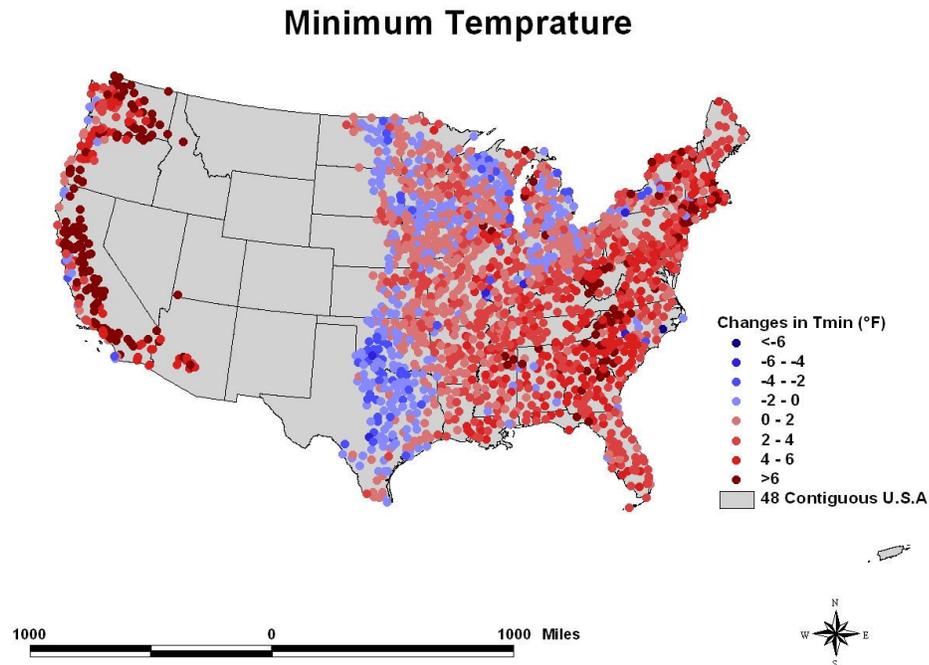
Minimum Temprature

The differences in monthly maximum temperatures between the observed and NNR values are slightly negative during all months of the year. The largest differences are seen in the fall. The difference in October, for example, is as high as 2.5 °F, compared with a yearly average decrease of 1.1 °F (for detailed results, see Figure 19). Nationwide, the differences in monthly maximum temperatures are somewhat negative in most of the country, but are strongly positive in California, Oregon, and Washington (see Figure 21). The urban effect is one of slight cooling, owing to shading, aerosols, and to thermal inertia differences between city and country that are not currently well understood (Kalnay and Cai 2003).

Figure 21: Long-Term Average Monthly Maximum Temperature Differences between Observed and NNR values (1970 - 1999)
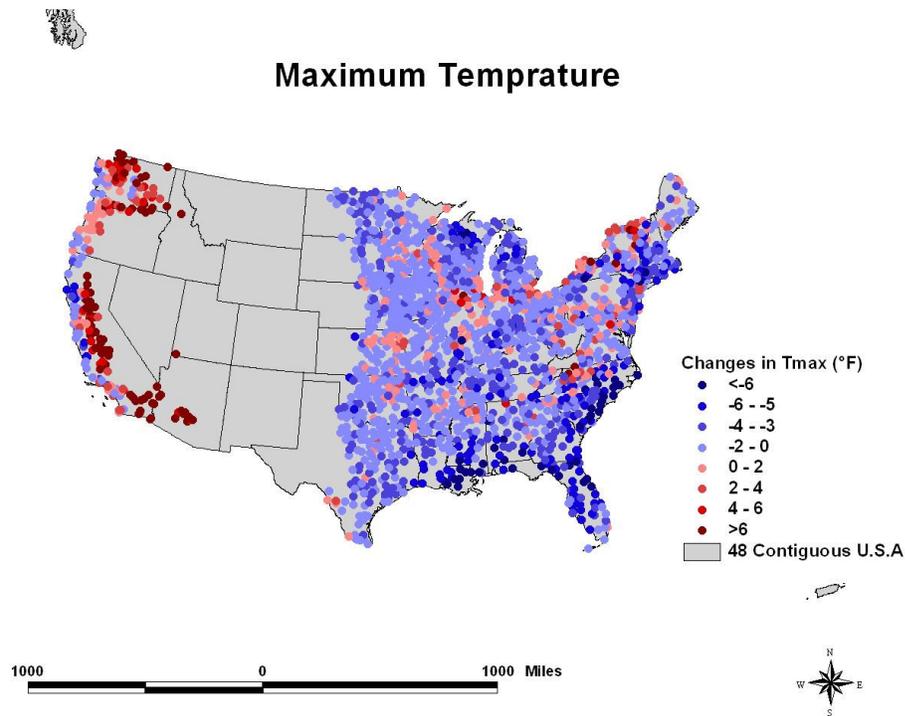
With strongly increased minimum temperatures and slightly decreased maximum temperatures, the net effect of the urban heat island imposes a reduced diurnal temperature range (DTR) and an increased monthly mean temperature. The strongest net effects of the heat islands are seen in the summer or warm half of the year, with the temperature increases up to 1.9 °F in June (for detailed results, see Figure 19). Nationwide, the differences in monthly mean temperatures are positive in most regions of the county, especially in the western coast and the north eastern U.S., but are somewhat negative in some parts of the country (see Figure 22). The latter phenomenon is usually referred to negative heat island, or urban cool island (UCI). The formation of UCI is currently not well understood, but is sometimes caused by

the inhabitation of early morning advection events of warm continent air in the urban

area (Morris and Simmonds 2000).

Figure 22: Long-Term Average Monthly Mean Temperature Differences between the
Observed and NNR values (1970 - 1999)

Mean Temprature
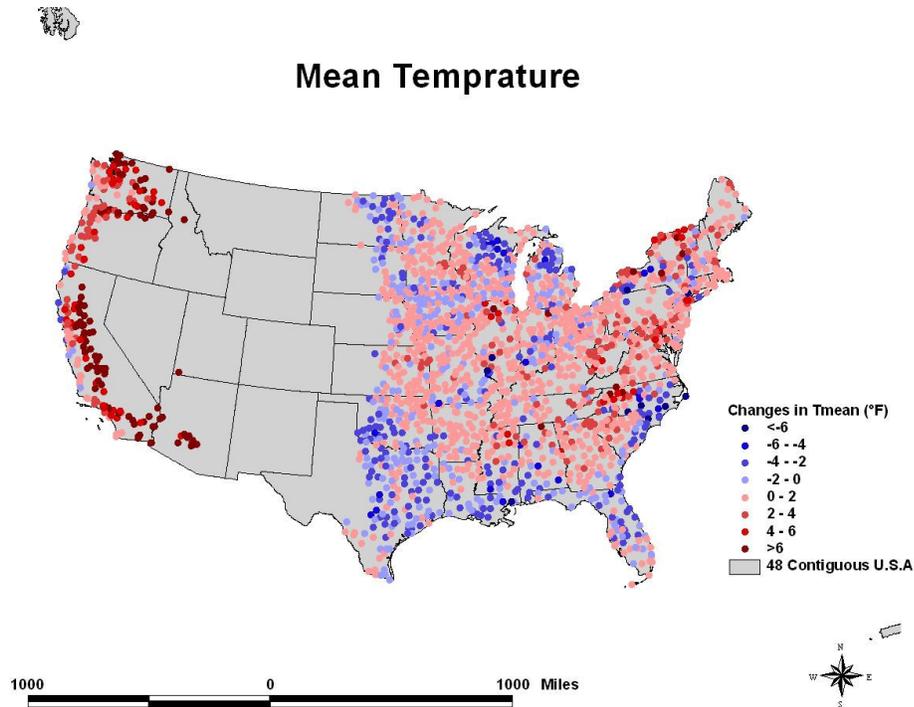
4. 3. 2 Changes in Degree-Days

To get a better picture on how heat island phenomena affect residential energy

use for space heating and cooling, it is more beneficial to look into the reduction in

heating degree-days and the increase in cooling degree-days rather than the

differences in minimum, maximum, and mean temperatures because the temperature

changes in non-heating or non-cooling seasons do not have any impact on residential

space-conditioning energy use.

This study shows that the differences between the observed and the NNR-derived heating degree-days are almost universally negative across all Census Divisions, while the differences in cooling degree-days are mostly positive. The nationwide average increase in cooling degree-days, for example, is 17 percent with a range from 3 percent to 233 percent, while the reduction in heating degree-days is 5 percent with a range from 3 percent to 49 percent (for detailed results, see Table 2).

Table 2: Comparison of Long-Term Average Heating and Cooling Days for the Observed Values Compared to the NNR Values by Census Division (1970 - 1999)

Division	Heating degree-days			Cooling degree-days		
	Observed	**NNR**	**% Diff**	**Observed**	**NNR**	**% Diff**
New England	7131	7471	-5%	286	164	74%
Middle Atlantic	6237	6617	-6%	476	349	36%
East North Central	6545	6578	-0.5%	519	504	3%
West North Central	6743	6793	-0.7%	667	681	-2%
South Atlantic	2734	2911	-6%	1719	1501	15%
East South Central	3106	3110	-0.1%	1519	1320	15%
West South Central	2251	2330	-3%	2261	2120	7%
Mountain	1675	3261	-49%	3321	1687	97%
Pacific	3453	4780	-28%	753	226	233%
National	**4672**	**4940**	**-5%**	**1113**	**951**	**17%**

Note: differences are shown as the percentages of NNR degree-days. All results reported here expect those in shaded areas are statistically significant with p-values less than 0.01.

These results are compatible with Taha et al.'s study (see Table 1) but with slightly lower estimates. This is expected because Taha et al.'s study is focused on single city while these results are based on Census Divisions and the numbers are more likely averaged down.

Figure 23 and 24 geographically show the differences between the observed and the NNR-derived heating and cooling degree-days. Nationwide, the differences in heating degree-days are negative in most of the country, while the differences in cooling degree-days are mostly positive, especially in the west coast and the north eastern regions.

Figure 23: Long-Term Average HDDs Differences between the Observed and NNR values (1990 - 1999)

Heating Degree Days
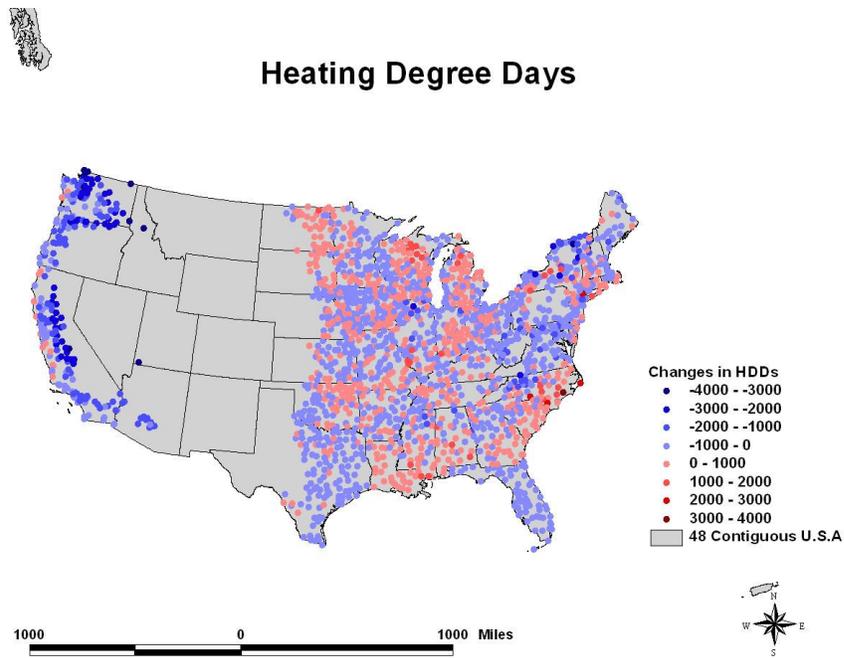
Figure 24: Long-Term-averaged CDDs Differences between the Observed and NNR values (1990 - 1999)

Cooling Degree Days
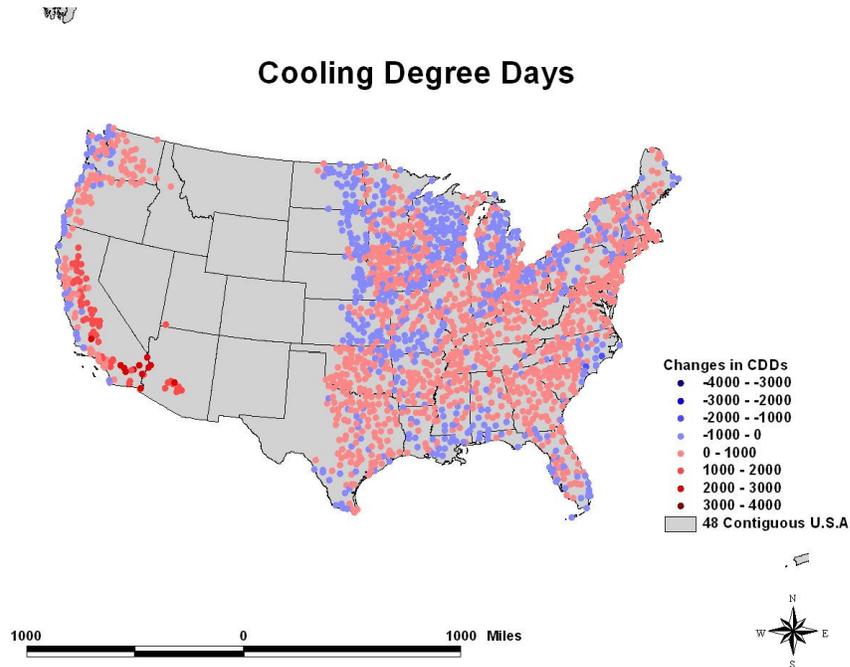
This study also looked into the differences between the observed and the NNR-derived heating and cooling degree-days in the four largest U.S. States. The results are consistent with previous findings: the effects of heat islands lead to the reduction in heating degree-days and the increase in cooling degree-days. Except Florida, the results for all the other three States are statistical significant and are reported in Table 3.

Table 3: Comparison of Long-Term Average Heating and Cooling Days for the
Observed Values Compared to the NNR Values by States (1970 - 1999)

Division	Heating degree-days				Cooling degree-days			
	Observed	NNR	Diff	% Diff	Observed	NNR	Diff	% Diff
NY	6820	7298	-478	-7%	315	217	98	45%
CA	2110	3273	-1163	-36%	1260	394	866	220%
TX	1407	1633	-226	-14%	2709	2564	145	6%
National	**4680**	**4933**	**-268**	**-5%**	**1112**	**953**	**162**	**17%**

Note: All results reported here are statistically significant with p-values less than 0.01.

4. 4 Impact of UHI on Residential Energy Use for Heating/Cooling

4. 4. 1 Heating/Cooling Energy Use Profiles

For the total delivered residential energy use, in the year of 2001, space
heating and cooling together account for more than half of the total, with 47 percent
for heating and 6 percent for cooling, respectively. For the total primary residential
energy use, the share of energy use for cooling is about 9 percent, larger than 6
percent, because air-conditioning equipment today are dominantly electricity-based
and there are a great deal of energy losses during both electricity generation and
transmission. For the shares of major end-uses of the total delivered and primary
residential energy, see Figure 25[2].

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[2] Total primary residential energy use by end-use shown in figure 21 is derived by the following two
information sources: first, the RECS provides delivered residential energy use data by both end-use
and fuel type; secondly, according to EIA'S Annual Energy Review, the ratio between residential
electricity sales and total energy used for electricity generation is around 0.44.

Figure 25: Total Delivered and Primary Residential Energy Use by Major End-uses, 2001 (Source: RECS 2001)
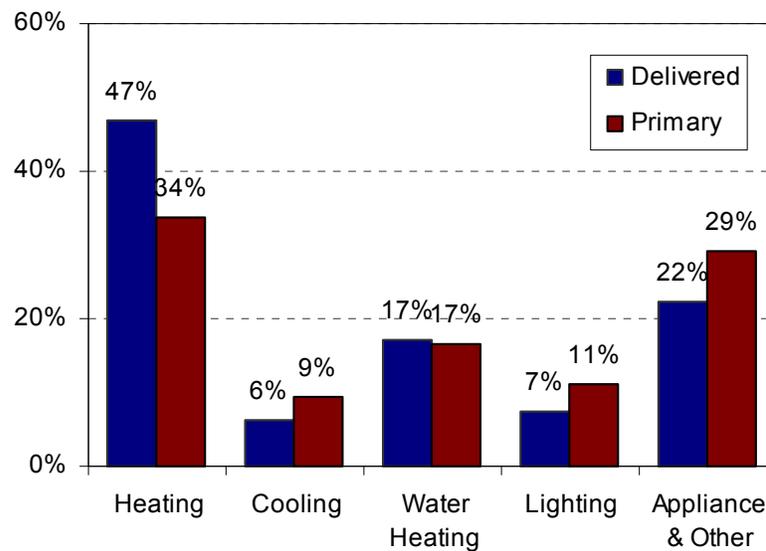
There are 99 percent of American households that heat their homes during winters. Natural gas is the most used fuel type. More than half of households use natural gas from underground pipes for heating. Electricity is the second most used fuel type and is more popular than natural gas in South Atlantic Division, while fuel oil is the third most used fuel type and is heavily used in New England Division and East South Central Division. Only 2 percent of American households still use wood as their main heating fuel today. Figure 26 sketches the shares of main fuel types used for heating. Figure 27 compares the shares of natural gas and electricity used as the major fuel for heating across U.S. Census Divisions.

Figure 26: Main Fuel Used for Heating Home, 2001 (Source: RECS 2001)
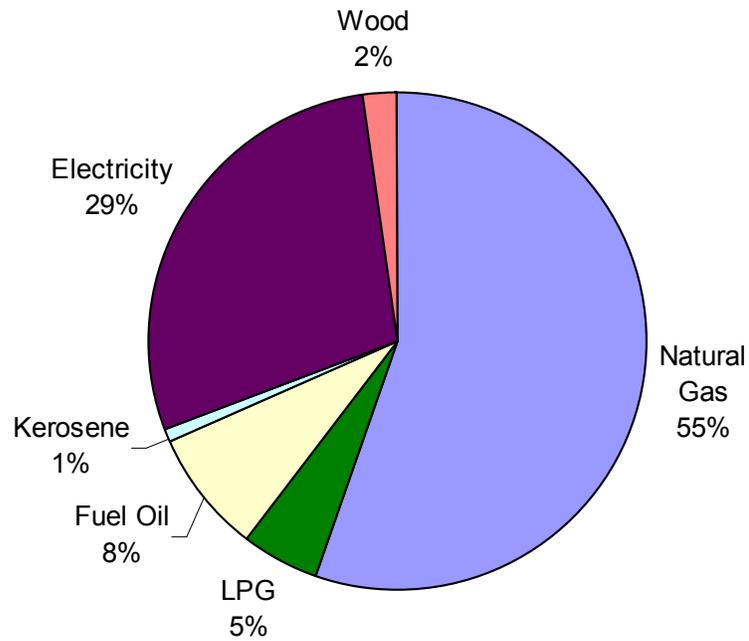
Figure 27: Shares of Natural Gas and Electricity Used as the Major Fuel to Heat Home by Census Division, 2001 (Source: RECS 2001)
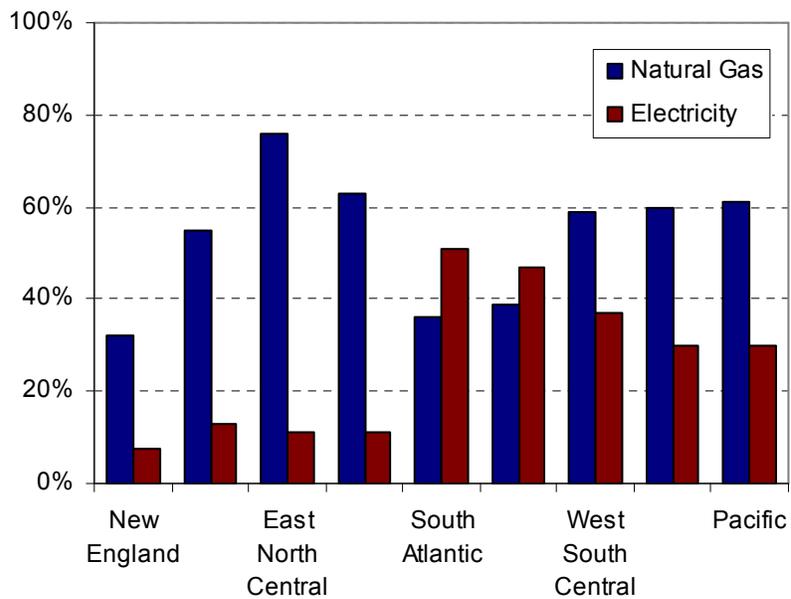
The most used heating equipment are central warm-air furnaces, followed by steam/hot water systems with radiators, heat pumps, built-in electric units installed walls, etc. The first two together account for three-fourths of all heating equipment used in American households. It was reported that about half of the heating equipment are 10 years or older and more than one-fourth of them are 20 years or older.

An average American household used around 50, 600 thousands of Btu of primary energy, or 46,000 thousands of Btu of delivered energy, for heating homes in 2001. The total amount of primary energy use for heating differs across U.S. Census Divisions. New England uses the most, approximately 72, 300 thousands of Btu of primary energy, while Pacific uses the least, only 32, 100 thousands of Btu of primary energy (see Figure 28).

Figure 28: Primary Residential Energy Use for Heating and Cooling by Census Division, 2001 (Source: RECS 2001)
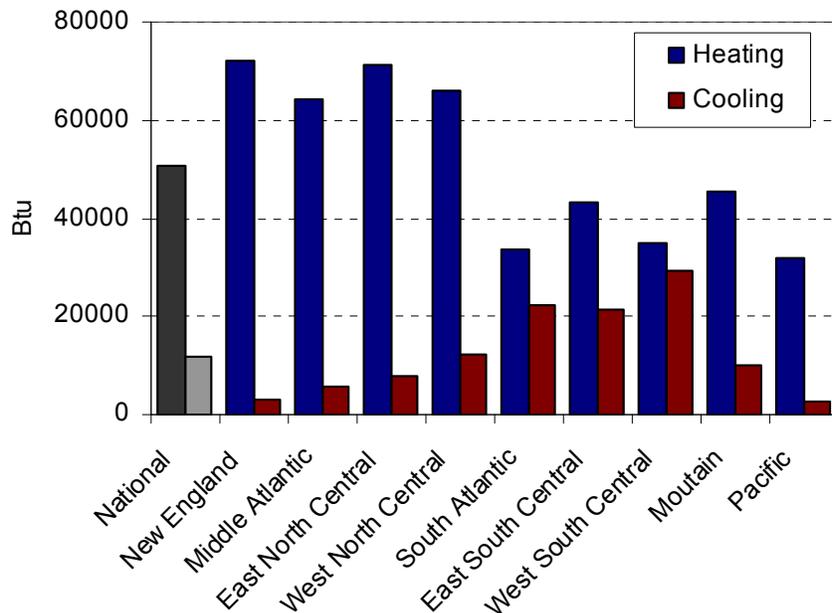
Around three-fourths of American households now use air-conditioning during summers. Two-thirds of them use central air-conditioning systems and the remaining one-third use individual AC units installed in the window or walls. All cooling equipment are electricity-based.   Compared with heating equipment, air-conditioning equipment are more updated. It was reported that about 40 percent of central air-conditioning equipment or 30 percent of individual AC units are 10 years or older and only 10 percent are 20 years or older.

In 2001 an average American household used around 11,900 thousands of Btu of primary energy, or 5,200 thousands of Btu of delivered energy, for cooling home. The amounts of primary energy use for cooling differ across U.S. Census Divisions. West South Central uses the most, approximately 29, 300 thousands of Btu of primary energy, while Pacific uses the least, only 2, 700 thousands of Btu of primary energy (see Figure 28).

4. 4. 2 Energy Use Change Due to Degree-day Change

To examine the dependence of the primary residential energy use for heating and cooling on heating and cooling degree-days, this study used OLS regression models to regress, respectively, the total primary energy use for heating and cooing after controlling the characteristics of housing units, the characteristics of households, total numbers of heating and cooling degree-days, the energy price, the status of heating or cooling equipment, etc.

As expected, the primary residential energy use for heating or cooling is strongly dependent on both housing unit characteristics and household characteristics. All else being equal, larger houses use more energy for heating and cooling. For

example, a household living in a 3000-square-feet house is expected to consume 15 percent more primary energy for heating and cooling than a household living in a 2000-square-feet house (see Table 11 of the Appendix for regression coefficients, t-ratios, and significance levels). The energy use also differs across different house type. Compared with households living in single-family detached housing, otherwise comparable households living in multi-family housing are expected to consume 39 percent less primary energy for space heating and 25 percent less for cooling, while households living in single-family attached housing are expected to consume 6 percent less for space heating and 14 percent less for cooling. Newly built houses are more energy efficient than old ones. The regression results indicate, for example, that otherwise comparable houses built after 1980 are expected to consume 34 percent less energy for heating that those built before 1940. But no statistical result is found on cooling. Households who reported their homes well insulated are also likely to consume significantly less energy for heating and cooling.

The space-conditioning energy use increases with annual household income, and varies by race/ethnicity. For example, black households consume 32 percent more primary energy for heating and 24 percent more for cooling than white households, while Asian households consume 15 less for heating and 21 percent less for cooling than white households. Households are expected to consume less primary energy for heating and cooling if they use relatively new heating/air-conditioning equipment, which are generally more energy efficient, and use heating/air-conditioning equipment with programmable thermostats.

The space-conditioning energy use decrease with energy price. The elasticity of total primary energy use for space heating and cooling per household per year with respect to energy price (dollar per thousand Btu) is around -0.6.

Controlling for all these covariates, the total primary energy use for space heating and cooling per household per year increases with total numbers of heating and cooling degree-days, respectively. With 95 percent confidence, for example, each ten heating degree-day increase is associated with a 0.2 percent increase in energy use for heating, while each ten cooling degree-day increase is associated with a 0.5 to 0.6 percent increase in energy use for cooling. In the year of 2001, an average American household consumed 52,200 thousands of Btu of primary energy for space heating and 16,600 thousands for cooling. These two facts above, taken together, indicate that each ten heating degree-day increase is associated 110 thousands of Btu of primary energy more for space heating, while each ten cooling-degree-day increase is associated with 90 thousands more for cooling (see Table 4).

Table 4: Additional Primary Energy Use (Thousands of Btu) for Heating and Cooling Associated with Each Ten- Heating-Degree-Day and Each Ten- Cooling -Degree-Day Increase (with 95% confidence interval)

State	Energy for Heating		Energy for Cooling	
	Lowest	Highest	Lowest	Highest
New York	51	155	31	73
California	44	69	54	72
Texas	65	108	122	227
Florida	73	121	103	232
National	**106**	**118**	**85**	**94**

This conclusion, however, cannot be universally applied to all States. Statistical models for such States as New York, California, Florida, and Texas show that for those States with a hot climate like Texas, each degree-day increase in cooling degree-days is associated significantly more energy use than the same degree-day increase in heating degree-days (see Table 4), while for those States with a cold climate like New York, each degree-day increase in heating degree-days is associated with significantly more energy use than the same degree-day increase in cooling degree-days. For the balance point temperature of 65 °F, one cooling degree-day increase may not trigger much energy demand for cooling for the States with temperatures usually below 75 °F during summertime, but a lot more for those States with temperatures often above 80 °F during summertime. Meanwhile, one heating degree-day increase may also not trigger much energy demand for heating for the States with temperatures usually above 50 °F during wintertime, but a lot more for those States with temperatures often below 35 °F during wintertime.

For the regression coefficients, t-ratios, and significance levels of these statistical models for the four States, see Table 12 of the Appendix.

4. 4. 3 Impact of UHI: Energy Rewards, or Energy Penalties?

Previous analyses in this study conclude with two findings: first, due to UHI formation, heating degree-days decrease in most regions of the country, with a national average value of 268 degree-days, while cooling degree-days increase, with a national average value of 162 degree-days; second, the total primary energy use for space heating and cooling increase with total numbers of heating and cooling degree-days, respectively. Regarding the total primary energy use, nationwide, one degree-

day increase in heating degree-days requires slightly more energy use than one degree-day increase in cooling degree-days, but in States with a hot climate like Texas, the conclusion is the opposite.

These two conclusions above, taken together, allow us to compare the net impact of heat island formation on primary residential energy use for space-conditioning. Nationwide, the UHI effect imposes a small energy reward due to less energy demand for heating during wintertime, the annual energy savings are about 1,500 thousands of Btu of primary energy, less than 3 percent of total primary energy use for space heating and cooling (see Table 5).

Table 5: The Net Impact of UHI on Residential Primary Energy Use per Household for Heating and Cooling (thousands of Btu) (with 95% confidence interval)

State	Δ Heating Energy (Thousands of Btu)		Δ Cooling Energy (Thousands of Btu)		Net Impact (Thousands of Btu)	
	Lowest	Highest	Lowest	Highest	Lowest	Highest
New York	-2426	-7426	304	717	-2122	-6709
California	-5088	-8016	4641	6271	-447	-1746
Texas	-1464	-2435	1764	3285	300	850
National	**-2839**	**-3160**	**1376**	**1518**	**-1463**	**-1641**

The energy reward due to heat island formation is most significant in States with a cold climate like New York. The energy savings per year range from 2,120 to 6,700 thousands of Btu of primary energy, about 3 to 10 percent of total primary energy use for space heating and cooling. In States with a hot climate like Texas, however, the UHI effect imposes a small energy penalty. The annual energy

penalties range from 300 to 850 thousands of Btu of primary energy, about 1 percent of total primary energy use for space heating and cooling.

4. 5 Impact of Sprawl on UHI Intensities

To examine the relationship between the UHI intensity and urban sprawl, this study used OLS regression models to regress the UHI intensities measured by the changes in heating and cooling-degree days after controlling county-specific variables such as the degree of sprawling, the size of population, the geographical location, and the topographic feature.

Otherwise comparable metropolitan counties in high-latitude areas, usually with a cold climate, are expected to have stronger effects of heat islands during wintertime, measured by the decrease in heating degree-days, while are expected to have weaker effects of heat islands during summertime, measured by the increase in cooling degree-days (see Table 13 of the Appendix for regression coefficients, t-ratios, and significance levels). Compared to counties in plains, otherwise comparable coastal counties are expected to have weaker effects of heat islands measured by the changes in both heating and cooling degree-days, while otherwise comparable counties at valleys are expected to have weaker effects of heat islands during summertime, measured by the increase in cooling degree-days, but have no significantly different effects of heat islands during wintertime, measured the reductions in heating degree-days. Holding the degree of sprawling and others constant, there is no statistically significant relationship found in this study between urban heat island intensities and the size of county population.

Controlling for all these covariates, the urban heat island effects measured by both the reduction in heating degree-days and the increase in cooling degree-days are stronger with the degree of compact, or weaker with the degree of sprawling. All else being equal, for example, each 10 percent increase in the county sprawl index is associated with a 12 percent reduction in the heat island intensity measured by the reduction in heating degree-days and an 11 percent increase in the heat island intensity measured by the increase in cooling degree-days. The urban heat island effects are stronger with 81 percent more reduction in heating degree-days and 71 percent more increase in cooling degree-days in compact counties, one standard deviation above the mean sprawl index, than in sprawling counties, one standard deviation below the mean index, with national average values of 217 heating degree-days and 115 cooling degree-days, respectively.

Although there is no statistical significant relationship found between the heat island intensity and the size of county population in the model that controls for the degree of sprawling, the relationship between these two is significant in the model that controls for the size of county area. Otherwise comparable metropolitan counties with more population have stronger effects of urban heat islands during both summertime and wintertime. All else being equal, for example, each ten percent increase in the size of county population is associated with a two percent increase in the heat island intensity measured by the reduction in heating degree-days and a 1.6 percent increase in the heat island intensity measured by the increase in cooling degree-days (see Table 14 of the Appendix for regression coefficients, t-ratios, and significance levels).

4. 6 Synthesis

Nationwide, the urban heat island phenomenon imposes a small energy reward on residential energy use for space heating and cooling, although the results may vary by State.

First, this study confirms that in most of the country heating degree-days decrease while cooling degree-days increase due to the urban heat island effects, with national average values of 268 heating degree-days and 162 cooling degree-days, respectively.

Second, the changes in degree-days could have an influential impact on residential space-conditioning energy use, which accounts for more than half of the total residential energy use. The regression results for the national models suggest that each hundred heating degree-day increase is associated with a 2 percent increase in energy use for heating, while each hundred cooling degree-day increase is associated with a 5 to 6 percent increase in energy use for cooling.

Third, these two conclusions above, taken together, allow us to compare the reduction in the energy demand for heating with the increase in the energy demand for cooling due to the heat island formation. This study indicates that the urban heat island phenomenon brings about energy savings on wintertime heating, and the annual savings are about 3,000 thousands of Btu of primary energy, accounting for 5 percent of the total for heating. Meanwhile, this study finds that the urban heat island phenomenon imposes energy penalties on summertime cooling, and the annual penalties are about 1,500 thousands of Btu of primary energy, approximately 8 percent of the total for cooling. Regarding the total primary energy use for space-

conditioning, this study discloses that nationwide, the net impact of the urban heat island phenomenon is a small energy reward, and the annual energy savings are about 1,500 thousands of Btu of primary energy, around 3 percent of the total for space heating and cooling. In addition, the energy reward is most significant in States with a cold climate like New York, ranging from 2,120 to 6,700 thousands of Btu of primary energy. In States with a hot climate like Texas, however, the heat island effect imposes a small energy penalty, ranging from 300 to 850 thousands Btu of primary energy, around 1 percent of the total for space-conditioning.

Last, the more compact a metropolitan county is, the stronger urban heat island effects does it expect to have. This study indicates that, for example, all else being equal, the urban heat island effects are stronger with 217 more heating degree-days reduction and 115 more cooling degree-days increase in compact counties, one standard deviation above the mean sprawl index, than in sprawling counties, one standard deviation below the mean index.

All these relationships above, taken together, allow us to relate urban sprawl to residential energy use, indirectly through the heat island formation. This study suggests that because of higher temperatures due to the heat island formation, an average household nationwide in compact counties, one standard deviation above the mean sprawl index, is expected to use about 4 percent less primary energy on space heating, around 2,400 thousands of Btu, than an average household in sprawling counties, one standard deviation below the mean index; meanwhile, they are expected to use approximately 6 percent more primary energy on summertime cooling, around

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1,000 thousands of Btu. The net annual primary energy saving is about 1,400

thousands of Btu for the household in compact counties.

This conclusion, however, cannot be universally applied to all States. In

States with a hot climate like Texas, for example, an average household in compact

counties, one standard deviation above the mean sprawl index, is expected to use

about 1,600 thousands of Btu of primary energy less on space heating than an average

household in sprawling counties, one standard deviation below the mean index;

meanwhile, they are expected to use approximately 1,800 thousands of Btu of

primary energy more on summertime cooling. The net annual primary energy penalty

is about 200 thousands of Btu for the household in compact counties.

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Chapter 5: Concluding Chapter

5. 1 Summary

This dissertation set up the concept framework to link urban sprawl to residential energy use, which is by far the first comprehensive study relating these two. As the conceptual framework described, urban sprawl could directly affect residential energy use because of potentially higher electricity transmission and distribution (T&D) losses, and could also indirectly affect residential energy use by having influential impacts on both housing stock and the formation of Urban Heat Islands (UHI).

The objective of this dissertation is to provide an original understanding of how urban sprawl might affect residential energy use. To achieve this goal, this dissertation addresses the following five sub-questions:

- *What is the impact of housing unit characteristics including house size and type on residential energy use?*

- *What is the impact of urban sprawl on housing stock?*

- *Do we experience urban heat island phenomena?*

- *Do urban heat island phenomena affect residential energy use? If so, do they impose an energy reward or an energy penalty?*

- *What is the impact of urban sprawl on urban heat island formation?*

In answering the first research question, an Ordinary Least Squared (OLS) regression model with STATA software was used to examine the dependence of

residential energy use on housing unit characteristics. The physical characteristics of housing units are found to have a strong relationship to residential energy use. Otherwise comparable residents of single-family detached housing are expected to consume 22 percent more primary energy than those of multifamily housing and 9 percent more than those of single-family attached housing. Larger houses use more energy than smaller ones. The elasticity of primary energy use with respect to floor area is 0.3. A household living in a 2000-square-feet house is expected to consume 38 percent more primary energy than a household living in a 1000-square-feet house.

In answering the second research question, hierarchical nonlinear and linear models with HLM 6 (Hierarchical Linear and Nonlinear Modeling) software were used to link urban sprawl to house type and house size, respectively. This dissertation found that households in sprawling counties are more likely to live in single-family detached housing and are expected to live in larger houses than households in compact counties. After controlling for both household and place covariates, for example, the odds of households living in multifamily or single-family attached rather than single-family detached housing are respectively 7 and 5 times higher for compact counties, one standard deviation above the mean sprawl index, than for sprawling counties, one standard deviation below the mean index. Meanwhile, otherwise comparable households in compact counties, one standard deviation above the mean sprawl index, have 19 percent less floor areas than households in sprawling counties, one standard deviation below the mean index.

In answering the third research question, this dissertation compared the long-term average monthly maximum, minimum, and mean temperatures of 1,982 surface

stations located below 500 meters over the forty-eight contiguous United States with the corresponding NNR-derived values from 1970-1999. These differences could be primarily attributed to urbanization and other changes in land use and thus reflect the temperature changes due to the formation of urban heat island (Kalnay and Cai 2003). Meanwhile, the long-term average heating and cooling degree-days derived from the observed surface temperatures were also compared with the long-term average heating and cooling degree-days derived from the corresponding NNR values. This dissertation demonstrated that urban heat island phenomena do occur. Due to the formation of urban heat island, the monthly minimum temperatures significantly increase over the most regions of the forty-eight contiguous United States, while the monthly maximum temperatures slightly decrease, which together result in the increased monthly mean temperatures. This dissertation also disclosed that due to urban heat island phenomena, the long-term average heating degree-days decrease in most regions of the country while cooling degree-days increase. Nationwide, there are 268 less heating degree-days and 162 more cooling degree-days, respectively.

In answering the fourth research question, this dissertation first used the OLS regression models with STATA software to respectively examine the changes in heating and cooling demand associated with each degree-day change in heating and cooling degree-days, called unit-degree-day changes in cooling and heating demand, and then derived, respectively, the total changes in heating and cooling demand by calculating the products of unit-degree-day changes in heating and cooling demand and the total changes in heating and cooling degree-days due to urban heat island phenomena. By comparing the total changes in heating and cooling demand, this

dissertation found that nationwide, urban heat island phenomena bring about a small energy reward on residential energy use, although the results may be different from State to State. Nationwide, annual energy savings on space heating due to urban heat island phenomena are about 3,000 thousands of Btu of primary energy, accounting for 5 percent of the total for heating, while annual energy penalties on cooling are about 1,500 thousands of Btu, approximately 8 percent of the total for cooling. Regarding the total primary energy use for space-conditioning, the annual energy savings due to urban heat island phenomena are about 1,500 thousands of Btu, around 3 percent of the total. The energy reward is most significant in States with a cold climate like New York, ranging from 2,100 to 6,700 thousands of Btu of primary energy. In States with a hot climate like Texas, however, urban heat island phenomena impose a small energy penalty, ranging from 300 to 850 thousands Btu of primary energy per year.

In answering the fifth research question, an OLS regression model with STATA software was used to examine the dependence of the urban heat island intensity on the degree of sprawling within major U.S. metropolitan counties. This dissertation indicated that the more compact a metropolitan county is, the stronger effect of the urban heat island is it expected to have. All else being equal, for example, the effects of urban heat islands are stronger with 217 more heating degree-days reduction and 115 more cooling degree-days increase in compact counties, one standard deviation above the mean sprawl index, than in sprawling counties, one standard deviation below the mean index.

5. 2 Synthesis

The first and second research questions address one focus of this dissertation: the indirect impact of urban sprawl on residential energy use through housing stock. The answers to the first two questions, taken together, allow us to relate urban sprawl to residential energy use indirectly through housing stock. This dissertation suggested that due to a higher likelihood of living in multifamily housing and living in a relatively smaller house, an average U.S. household would likely consume about 13 percent less primary energy living in a compact county, one standard deviation above the mean sprawl index, than in a sprawling county, one standard deviation below the mean index,. That is about 17,900 thousands of Btu of primary energy saving per year per household.

The last three research questions together address the other focus of this dissertation: the indirect impact of urban sprawl on residential energy use through the formation of urban heat islands. The answers to the three questions, taken together, allow us to relate urban sprawl to residential energy use indirectly through urban heat island formation. This dissertation found that because of higher temperatures due to urban heat island phenomena, nationwide, an average household in compact counties, one standard deviation above the mean sprawl index, is expected to use about 1,400 thousands of Btu of primary energy less on space-conditioning than an average household in sprawling counties, one standard deviation below the mean index. This conclusion, however, cannot be universally applied to all States. In States with a hot climate like Texas, for example, an average household in compact counties, one standard deviation above the mean sprawl index, is expected to use 200 thousands of

Btu of primary energy more on space-conditioning than an average household in sprawling counties, one standard deviation below the mean index.

These two findings, taken together, allow us to derive the net impact of urban sprawl on residential energy use. Nationwide, an average U.S. household in compact counties, one standard deviation above the mean sprawl index, is expected to use 14 percent less, about 19,300 thousands of Btu of primary energy, than an average household in sprawling counties, one standard deviation below the mean index. The energy savings are mostly due to households' higher likelihoods of living in multifamily housing and less demand for floor areas. The indirect impact of urban sprawl on residential energy use through housing stock is in the same direction of the other indirect impact through urban heat island formation, and both of them impose energy penalties on residential energy use. For States with a hot climate like Texas, although urban sprawl brings about a small energy reward on space-conditioning energy use because of urban heat island formation, the saving is negligible compared to the penalty due to the impact of housing stock. An average household in compact counties in Texas, one standard deviation above the mean sprawl index, is expected to use around 14 percent less, about 17,700 thousands of Btu of primary energy, than an average household in sprawling counties, one standard deviation below the mean index.

5. 3 Policy Implications

Several policy implications emerge from this dissertation, including the important role of compact land-use development patterns as a demand-side measure

in prompting sustainable residential energy consumption, the need to keep away from extreme compactness in urban land-use planning to avoid unwanted severe consequences of strong effects of urban heat islands, and the choices we are facing now between living bigger and living smart.

5. 3. 1 Compact Land-use Developments

The first policy implication that emerged from this dissertation is an important role that urban land-use planning could play as a demand-side measure to reduce residential energy consumption. Improving energy efficiency of home appliances and equipment, as one of the most important supply-side measures, has been the central paradigm of U.S. energy policy for many years. During the period of the first energy crisis from the late 1970s to the early 1980s, the U.S. Department of Energy was created and Congress passed the legislation that laid the groundwork for future energy policies. This groundwork evolved into the use of codes and standards and the deployment of improved technologies to acquire energy efficiency resources. Since mid-1990s, "market transformation" has emerged as a key approach for achieving energy efficiency in a competitive, market-based environment. One good example is the deregulation of U.S. power market.

Such energy polices as energy labeling and energy efficiency standards for household appliances have undoubtedly been successful in improving energy efficiency and reducing energy consumption. For example, it is estimated that the U.S. federal residential energy efficiency standards taking effect in the 1988–2007 period will reduce residential primary energy consumption by 8–9 percent in 2020

compared to the levels expected without any standards (Meyers, McMahon et al. 2003).

However, the challenge of solving looming crises associated with fossil fuel dependence and resulting greenhouse gas accumulation demands that we target absolute and not just relative, reductions in energy demand. Improving energy efficiency means providing more service per a fixed amount of energy consumed but does not necessarily mean using less energy. Indeed, with rebound effects, efficiency gains may trigger more energy use over time. In addition, as documented in chapter 1 of this dissertation, there is already evidence that advances in technology alone will be neither sufficient nor timely enough to achieve sustainable residential energy consumption. For example, despite increasing energy efficiency, the total primary residential energy use per capita has been gradually increasing since the early 1980s, and per-capita residential carbon dioxide emissions have also been gradually increasing since 1990s (see Figure 1 in chapter 1). Moreover, energy efficiency can likely play only a minimal role in meeting future energy needs (Lightfoot and Green 2001), and that historic increases in the energy efficiency may not likely be sustained into the future (Siderius 2004).

To be noted, since the late 1990s there has been the shift in focus from supply-side measures to demand-side measures or from a device-centered view to a people-and-devices view. One good example is the use of land-use planning as a demand-side measure to reduce transportation energy use. It has recently been receiving more and more attention that the energy use and greenhouse gas emission in the transportation sector could be significantly reduced through implementing improved

land-use planning, such as more compact and mixed-use developments served by efficient transit networks and walking-and-bicycling-favored microscale urban design features, rather than simply improving the efficiency of individual modes of transportation (Ewing 1994; Ewing 1995; Kessler and Schroeer 1995; Burchell, Listokin et al. 1998; Bento, Cropper et al. 2003).

Compared to the transportation sector, however, there have been only a few attempts to use demand-side measures in the residential sector, including some campaign and programs targeting changes in consumers' habits and practices such as turning off unused equipment. There is by far no comprehensive study exploring whether or not there are potential residential energy savings through implementing improved land-use planning policies. This dissertation concluded with a positive answer to this question: promoting compact land-use developments could encourage more multifamily or single-family detached housing and discourage households' excessive demands for floor areas to achieve a sustainable growth in residential energy consumption. In this dissertation, households of compact counties are found to use less energy at home than households of sprawling counties mostly due to their higher likelihoods of living in multifamily housing and less demand for floor areas. The magnitudes of savings are not only largely dependent on the compactness of the county in which the households live but also on the "coldness" or "hotness" of the place because of urban heat island phenomena. For example, the dissertation disclosed that an average U.S. household in compact counties, one standard deviation above the mean sprawl index, would likely consume 13 percent less primary energy

than an average household in sprawling counties, one standard deviation below the mean index.

If the trend of smaller household size continues (Laurence 2004) and improvement rates of energy efficiency in practice keep the annual increasing trend less than 1 percent (Blok 2005), the important role of promoting compact land-use developments would especially stand out as one important demand-side measure to reduce residential energy consumption.

5. 3. 2 Not Too Sprawled, Not Too Compact

The second policy implication emerged from this dissertation is the need to keep away from extreme compactness in urban land-use planning to avoid unwanted severe consequences from strong effects of urban heat islands. The relationship among urban sprawl, urban heat island formation, and residential energy consumption disclosed in this dissertation suggests that a compact a county is expected to have stronger urban heat island effects. The energy demand for summertime cooling could be significantly higher with incredibly increased compactness, especially in States with a hot climate like Texas. Even the modest increase in the strength of urban heat island effects due to the modest increase in compactness could have significant implications for the reliability of electric power systems. In addition, strong urban heat island effects could exacerbate heat stress and impose other threats on human health.

First, the urban heat island effects are more likely to increase with the compactness of a county and lead to significantly higher energy demand for summertime cooling, especially in States with a hot climate like Texas. This

dissertation found, for example, that in States with a hot climate like Texas the urban heat island phenomenon imposes 1,800 to 3,300 more thousands of Btu of primary energy for summertime cooling, accounting for 5 to 9 percent of the total for cooling. In a relatively extreme case, if assuming the compactness of a county in Texas increases 217 percent from two standard deviations below the mean to two standard deviations above the mean, the increase in compactness would be associated with 315 more cooling degree-days and thus lead to 3,850 to 7,150 more thousands of Btu of primary energy for summertime cooling, about 10 to 19 percent increase from before.

Second, even the modest increase in the strength of urban heat island effects could push up peak electric demand and thus may be significant enough to warrant changes in peak load capacity planning for the region. Weather tends to be the most important driver of peak demand, which refers to the maximum electric load at a specified point in time. For utilities in warmer regions of the United States, peak demand is driven mainly by air conditioning loads on the hottest summer afternoons (Koomey and Brown 2002), in which the well-known urban heat island effect is usually strongest (Morris, Simmonds et al. 2001; Voogt 2004).

Last, besides higher energy demand for cooling, urban heat island phenomena affect the environment and population in a number of ways, including the degradation of air quality, higher frequencies of extreme heat-stress events, the triggering of adverse meteorological events, and indirectly promoting sprawl further (Ruth and Rong 2005).

5. 3. 3 Living Bigger or Living Smarter

The last but not least policy question emerged from this dissertation is to raise the question: should we live bigger or live smarter?

In this dissertation residents of sprawling metro areas are found to be more likely to live in single-family detached rather than attached or multifamily housing, and are also expected to live in bigger houses. The process of sprawling has been experienced in most U.S. metropolitan areas in past decades. During the same period, we have seen that the average household size has been steadily declining while the average home has been getting increasingly larger. For example, the size of new houses in 2005 increased to 2,433 square feet on average from 2,349 square feet in 2004, according to the National Association of Home Builders (NAHB). That is up from 2,095 square feet in 1995, 1,905 square feet in 1987, and a mere 1,660 in 1973.

Extra space is definitely associated with an extra energy cost burden, a conclusion that is confirmed by the findings of this dissertation, and is also aligned with people general intuition. The question is why most Americans seem to be accepting the extra energy cost burden in exchange for extra space. First, many people may not think through the costs of maintaining such extra space. They put the focus on initial costs as opposed to lifetime utility costs. According to NAHB's Consumer Preference Survey 2003-2004, when asked how much extra they would be willing to pay upfront in the purchase price of a home to save $1,000 every year in utility costs, 62 percent of people said between $5,000 to $10,000; while 27 percent said they would not pay more than $4,999 above the purchase price to save themselves $1,000 a year (Gerencher, K. 2006). Second, some people may just not

realize the costs until they receive large energy bills. Other people who buy so-called McMansions or build massive additions to their homes likely have enough wealth to absorb energy price shocks. If the energy price remain high and continues to climb, however, there will be some gradual or rapid market shifts towards more recognition of operation and maintenance cost.

Let alone the imposed extra energy cost burden and extra cleaning time, the extra space does not necessarily bring about more comfort or happiness. The space itself, however, has no direct relationship with comfort. Small but well-designed homes could result in much more comfort to people than larger but poorly designed ones. It is the responsibility of scholars, architectures, government officials, and members of the private sector alike to work together to build more attractive, small but well-designed houses and to promote the philosophy of "living smart rather than living bigger."

5. 4 Avenues for Future Research

This dissertation offered original insights on another impact of urban sprawl, that is, the impact of sprawl on residential energy use. While the dissertation set up the conceptual framework linking urban sprawl to residential energy use and provided important conclusions and analyses relating to urban sprawl, housing, and the formation of urban heat islands, it also raised additional questions that point to new avenues for future research.

One avenue for future research is to directly regress residential primary energy use per capita in major U.S. metropolitan counties by using hierarchical linear

models against both disaggregate household-level variables such as household income and the number of household members and aggregate county-specific variables such as the degree of sprawling within these counties and the observed heating and cooling degree-days. This approach makes it clearer to get the quantitative relationship between the degree of sprawling and per-capita residential energy use. This benefit, however, is at the expense of losing the opportunity to disclose the dynamics by which urban sprawl affects residential energy use, which by contrast is the focus of this dissertation and was also explored in detail.

There are great benefits in future research to directly link residential energy use to the degree of sprawling within counties and to compare the results with the findings of this dissertation. But the possibility to conduct such research is dependent on data availability. The Energy Information Administration's Residential Energy Consumption Survey is the most comprehensive national source of residential energy use data, but it has a limited sample size and does not have the necessary data coverage to make statistically-valid county-level analyses for the entire United States. For the long run, such a large-scale national database with the necessary data coverage reporting consumer activities (home energy use, housing unit characteristics, and household expenditures on housing operation, etc.) will be helpful to explore residential energy use and environmental impacts relating to urban land-use patterns, and to provide effective suggestions on how to reduce energy use and reduce its impacts.

Another avenue for future research is to expand the sample size of the sprawl and UHI model, which analyzes the relationship between the urban heat island

intensity and the degree of sprawling. In this dissertation, the sprawl and UHI model

mostly covers those non-mountainous metropolitan counties due to data availability.

By expanding the sample size to fully cover all major U.S. metro counties with

available corresponding measures of urban heat island intensities, the future research

could further verify the conclusion from this dissertation and have a better understand

of the relationship between urban sprawl and the formation of urban heat islands.

In addition, while this dissertation modeled the urban heat island intensities by

controlling for such county-specific characteristics as the degree of sprawl, the size of

county population, geographic location, and topographic features, it also raised the

question of whether or not those controls are inclusive; that is, whether or not the

sprawl and UHI model in this dissertation has controlled for all important factors that

could have an influential impact on the formation of urban heat islands. There has

been considerable advancement in the understanding of urban climatology in the last

15 years. There are three different scales for looking into the urban heat island. The

first is mesoscale of the whole area. The second is the local scale such as the size of a

park. The third scale is the microscale of the garden and buildings near the

meteorological observing site (Perterson 2003). This dissertation looked into the

urban heat island intensities of about 500 metropolitan counties nationwide and only

focused on the first mesoscale level. The local and microscale factors could have

influential impacts on the urban heat island intensities such as whether or not there

are large city parks and lakes in the county. By not modeling these factors, this

dissertation may overestimate or underestimate the impact of urban sprawl on the

urban heat island intensities. In taking the local and microscale factors into

consideration, future researchers could better understand the impact of urban sprawl on the urban heat island intensities.

The last avenue for future research is to explore further other potential factors linking urban sprawl to residential energy use. As the conceptual framework in this dissertation demonstrated, urban sprawl could have an influential impact on electricity transmission and distribution. This dissertation used a uniform ratio during the conversion from the total electricity retail sales to the total primary energy use for electricity generation. The ratio, in fact, might be significantly different across metropolitan counties with different degree of sprawling. In addition, urban sprawl, or urban land-use patterns could also affect residents' energy choices. A good example is distributed electricity generation (DG), which refers to the power generation sited at the "load." Incorporating DG to provide electricity, light, heat, or mechanical energy at the point of use offers many advantages including no requirement for costly installation of new transmission lines, reduction in energy delivery losses, promoting the use of renewable resources, and eliminating potential brown-outs or black-outs. How would these advantages potentially reduce the negative impact of urban sprawl? Future research could assist public utility policymakers in planning energy supply systems according to region's different land-use patterns.

Appendix

Table 6: Descriptive Statistics of Variables in the RECS 2001, the PUMS 2000, and the AHS 1998, 2002

	2001 RECS		2000 CENSUS		1998, 2002 AHS	
	Mean	(SD)	Mean	(SD)	Mean	(SD)
Household Variables						
Primary Energy Use per HH *(Thousands of Btu)*	95,415	(58,093)	-	-	-	-
House Size *(square feet)*	2,097	(1,410)	-	-	1,689	(1,098)
House Type						
Single-Detached	60.5%	-	60.7%	-	65.5%	-
Single-Attached	10.4%	-	7.6%	-	12.4%	-
Multifamily	29.1%	-	31.7%	-	22.1%	-
Built Year						
1939 or Before	30.1%	-	14.3%	-	10.7%	-
1940 to 1959	20.7%	-	23.4%	-	18.9%	-
1960 to 1979	23.9%	-	32.5%	-	36.4%	-
1980 to 2000	25.3%	-	29.7%	-	34.0%	-
# of Household Members						
Child	0.51	(0.93)	0.71	(1.11)	0.71	(1.10)
Adult	2.11	(1.07)	1.95	(0.91)	1.92	(0.83)
Household Income	38.7%	-	30.5%	-	28.4%	-
Less than 3k	24.7%	-	21.5%	-	20.8%	-
30k ~ 50k	20.7%	-	19.8%	-	19.5%	-
50k ~ 75k	15.9%	-	28.2%	-	31.4%	-
75k or more						
Race of Householder	70.7%	-	69.0%	-	71.3%	-
White	12.8%	-	13.4%	-	10.4%	-
Black	10.9%	-	12.3%	-	11.5%	-
Hispanic	3.5%	-	5.1%	-	5.2%	-
Asian	2.1%	-	1.9%	-	1.6%	-
Others						
County Variables						
County Sprawl Index	-	-	107	(28)	110	(21)
Residential Construction Cost	-	-	0.982	(0.145)	0.992	(0.130)
Total Population in MSAs	-	-	4,470,225	(5,782,837)	4,066,947	(4,126,514)

Data Source: EIA's Residential Energy Use Survey 2001, U.S. Census Bureau's PUMS 2000, U.S. Census Bureau's American Housing Survey 1998 and 2002, and County Sprawl Index (Ewing, Schmid et al. 2003).

Table 7: Relationship between Household Characteristics, Housing Unit Characteristics, and Residential Primary Energy Use (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of Primary Residential Energy Use per Household per Year (Thousands of Btu)

	Coefficient	*t*	*p*
Ln (Floor Space) (square feet)	0.321	23.8	<0.001
House Type			
Single-Family Attached	-0.094	-4.8	<0.001
Multifamily	-0.244	-12.8	<0.001
Year Built			
1940 to 1959	-0.045	-2.3	0.019
1960 to 1979	-0.053.	-2.8	0.006
1980 to 2000	-0.090	-4.4	<0.001
Number of Household Members			
Child (less than 16)	0.116	6.0	<0.001
Adult (16 or older)	0.164	7.2	<0.001
Household Income			
30k - 50k	0.042	2.5	0.012
50k - 75k	0.068	3.8	<0.001
75k or more	0.153	7.6	<0.001
Race of Householder			
Black	0.088	4.8	<0.001
Hispanic	-0.182	-8.0	<0.001
Asian	-0.234	-6.1	<0.001
Others	-0.172	-3.7	<0.001
Heating Degree Days	0.00015	8.9	<0.001
Cooling Degree Days	0.00031	12.5	<0.001
Ln (Weighted-Energy Price) (dollar per thousand Btu)	-0.340	-11.9	<0.001
R-Squared		0.6529	
Number of Households		3725	

Note:

1) Reference dummies included single-family detached housing, houses built in before 1940, households with annual household income less than $30,000, and white householders.

2) Other controls included the square term of heating and cooling-degree days and the square term of number of household adults and household children.

Data Source: EIA's Residential Energy Use Survey 2001.

Table 8: Relationship between Household Characteristics, Urban Sprawl, and House Type – Random Intercept Model (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Odds of Residents Living in Different Type of Housing
Reference Category: Single-family Detached Housing

	Single-Family Attached			Multifamily		
	Coefficient	*t*	*p*	**Coefficient**	*T*	*p*
Year Built						
1940 to 1959	-0.440	-7.0	<0.001	-0.551	-8.4	<0.001
1960 to 1979	0.362	3.8	<0.001	0.575	6.2	<0.001
1980 to 2000	1.168	11.9	<0.001	0.854	9.4	<0.001
Number of Household Members	-0.203	-8.4	<0.001	-0.357	-21.9	<0.001
Child	-0.698	-17.2	<0.001	-1.124	-32.4	<0.001
Adult						
Household Income						
30k - 50k	-0.106	-6.6	<0.001	-0.466	-29.6	<0.001
50k - 75k	-0.372	-13.6	<0.001	-1.015	-36.7	<0.001
75k or more	-0.874	-28.8	<0.001	-1.791	-35.6	<0.001
Race of Householder						
Black	0.592	10.5	<0.001	0.716	15.3	<0.001
Hispanic	0.713	11.3	<0.001	1.077	15.6	<0.001
Asian	0.297	4.7	<0.001	0.689	10.9	<0.001
Others	0.145	4.2	<0.001	0.545	15.1	<0.001
County Variables						
Ln (Sprawl Index)	2.980	9.4	<0.001	3.810	12.6	<0.001
Ln (Residential Construction Cost)	2.293	5.9	<0.001	1.538	4.9	<0.001
Ln (Total Population)	-0.405	0.8	0.432	-1.003	-0.2	0.831
Number of Households (Household-Level)	2,519,726					
Number of Counties (County-Level)	266					

Note:

1) The above regression results were estimation of fixed effects with robust standard errors.

2) Reference dummies included houses built in before 1940, households with annual household income less than $30,000, and white householders.

3) Other controls included the square term of number of household adults and children.

Data Source: the U.S. Census PUMS 2000, County Sprawl Index (Ewing, Schmid et al. 2003), and R. S. Means' Residential Cost Data, 20th Annual Edition

Table 9: Relationship between Household Characteristics, Urban Sprawl, and House Type – Random Coefficients Model (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of Odds of Residents Living in Different Type of Housing
Reference Category: Single-family Detached Housing

	Single-Family Attached			Multifamily		
	Coefficient	t	P	Coefficient	t	p
Household Income						
30k - 50k						
INTERCEPT	-0.184	-14.2	<0.001	-0.525	-39.7	<0.001
Ln (Sprawl Index)	-0.028	-0.5	0.611	0.279	3.5	0.001
50k - 75k						
INTERCEPT	-0.430	-23.1	<0.001	-1.147	-55.7	<0.001
Ln (Sprawl Index)	0.220	2.5	0.015	0.673	5.9	<0.001
75k or more						
INTERCEPT	-0.600	-21.9	<0.001	-1.986	-74.5	<0.001
Ln (Sprawl Index)	0.241	1.4	0.178	1.232	8.9	<0.001
Race of Householder						
Black						
INTERCEPT	0.961	33.9	<0.001	0.487	17.2	<0.001
Ln (Sprawl Index)	-1.173	-5.9	<0.001	-1.032	-5.5	<0.001
Hispanic						
INTERCEPT	1.329	35.9	<0.001	0.856	25.0	<0.001
Ln (Sprawl Index)	-1.017	-5.2	<0.001	-0.961	-5.2	<0.001
Asian						
INTERCEPT	1.077	35.6	<0.001	0.834	29.0	<0.001
Ln (Sprawl Index)	-1.103	-5.8	<0.001	-1.033	-5.5	<0.001
Others						
INTERCEPT	0.577	23.1	<0.001	0.251	9.2	<0.001
Ln (Sprawl Index)	-0.567	-2.6	0.010	-0.488	-2.7	0.008
Ln (Sprawl Index)	1.705	4.5	<0.001	2.566	6.6	<0.001
Number of Households (Household-Level)	2,519,726					
Number of Counties (County-Level)	266					

Note:

1) The above regression results were estimation of fixed effects with robust standard errors.

2) Reference dummies included houses built in before 1940, households with annual household income less than $30,000, and white householders.

3) Other controls at the household level included built year of houses, number of household adults and children, and the square term of number of household adults and children. Other controls at the county level included residential construction cost index and total population in each metro area.

Data Source: the U.S. Census PUMS 2000, County Sprawl Index (Ewing, Schmid et al. 2003), and R. S. Means' Residential Cost Data, 20th Annual Edition

Table 10: Relationship between Household Characteristics, Urban Sprawl, and House Size – Random Intercept Model (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of Square feet of Housing Units

	Coefficient	t	p
House Type			
Single-Family Attached	-0.474	-23.5	<0.001
Multifamily Home	-0.678	-44.3	<0.001
Year Built			
1940 to 1959	-0.045	-3.3	<0.001
1960 to 1979	0.096	5.8	<0.001
1980 to 2000	0.201	10.6	<0.001
Number of Household Members			
Non-adult (less than 18)	0.010	2.5	0.013
Adult (18 or older)	0.121	12.1	<0.001
Household Income			
30k - 50k	0.074	7.1	<0.001
50k - 75k	0.144	11.0	<0.001
75k or more	0.297	19.1	<0.001
Race of Householder			
Black	-0.095	-3.7	<0.001
Hispanic	-0.135	-9.7	<0.001
Asian	-0.034	-2.8	0.006
Others	-0.071	-4.5	<0.001
County Variables			
Ln (County Sprawl Index)	-0.402	-2.0	0.046
Ln (Residential Construction Cost)	0.111	0.8	0.421
Ln (Total Population)	-0.002	-0.1	0.944
Number of Households (Household-Level)	61,947		
Number of Counties (County-Level)	59		

Note:

1) Reference dummies included houses built in before 1940, households with annual household income less than $30,000, and white householders.

2) Other controls included year 2002 dummy variable and the square terms of number of household adults and children.

Data Source: the U.S. Census American Housing Survey 1998 and 2002, County Sprawl Index (Ewing, Schmid et al. 2003), and R. S. Means' Residential Cost Data, 20th Annual Edition

Table 11: Relationship between Heating and Cooling Degree-Days and Residential Primary Energy Use for Heating and Cooling – National Model (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of Primary Residential Energy Use for Heating or Cooling per Household per Year (Thousands of Btu)

	Heating			Cooling		
	Coefficient	*t*	*p*	**Coefficient**	*t*	*p*
Heating/Cooling Degree Days	0.00021	36.6	<0.001	0.00054	40.0	<0.001
Floor Space (square feet)	0.00014	15.9	<0.001	0.00014	16.0	<0.001
House Type						
Mobil home	0.058	1.7	0.087	0.090	1.8	0.067
Single-Family Attached	-0.061	-2.1	<0.001	-0.153	-3.3	<0.001
Multifamily	-0.502	-18.7	<0.001	-0.282	-8.1	<0.001
Year Built						
1940 to 1959	-0.181	-6.3	<0.001	-0.037	-1.0	0.301
1960 to 1979	-0.302	-11.3	<0.001	-0.024	-0.7	0.492
1980 to 2000	-0.410	-14.2	<0.001	-0.030	-0.8	0.398
Main Fuel						
Electricity	0.287	6.2	<0.001	-	-	-
Fuel oil	-0.064	-2.1	0.040	-	-	-
Others	-0.164	-3.3	<0.001	-	-	-
Household Income						
30k - 50k	0.023	1.0	0.310	0.023	1.0	0.310
50k - 75k	0.024	1.0	0.336	0.024	1.0	0.336
75k or more	0.143	4.9	<0.001	0.143	4.9	<0.001
Race of Householder						
Black	0.274	9.6	<0.001	0.217	6.5	<0.001
Hispanic	-0.116	-3.3	0.001	-0.080	-1.8	0.066
Asian	-0.166	-3.2	0.001	-0.233	-3.2	0.002
Others	-0.012	-0.2	0.866	0.035	0.4	0.688
Ln (Energy Price) (dollar per thousand Btu)	-0.599	-11.1	<0.001	-0.612	-4.7	<0.001
R-Squared	0.6330			0.6817		
Number of Households	4666			3464		

Note:
1) Reference dummies included single-family detached housing, houses built in before 1940, natural gas as the main heating fuel, households with annual household income less than $30,000, and white householders.

2) Other controls included the age of heating or cooling equipment variable (dummies as less or more than 10 years old), the programmability of the thermostat of heating or cooling equipment variable (dummies as yes or no), the building insulation variable (dummies as well or poorly insulated), if the cooling equipment is central or not, and if there is someone at home all day on a typical weekday (dummies as yes or no).

Data Source: EIA's Residential Energy Use Survey 2001.

Table 12: Relationship between Heating and Cooling Degree-Days and Residential Primary Energy Use for Heating and Cooling – State Model (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of Primary Residential Energy Use for Heating and Cooling per Household per Year (Thousands of Btu)

	Heating			*Cooling*		
	Coefficient	*t*	*p*	**Coefficient**	*T*	*p*
New York						
Heating/Cooling Degree Days	0.00016	3.9	<0.001	0.00097	4.9	<0.001
R-Squared	0.6286			0.4681		
Number of Households	320			208		
California						
Heating/Cooling Degree Days	0.00022	8.8	<0.001	0.00084	13.3	<0.001
R-Squared	0.5705			0.7406		
Number of Households	488			224		
Texas						
Heating/Cooling Degree Days	0.00026	7.9	<0.001	0.00054	6.6	<0.001
R-Squared	0.6706			0.6053		
Number of Households	289			275		
Florida						
Heating/Cooling Degree Days	0.00102	8.1	<0.001	0.00044	5.2	<0.001
R-Squared	0.7496			0.6027		
Number of Households	163			172		

Note: Besides heating and cooling degree-days, other controls included in the State model above are the same as those included in the national model (see table 11).

Data Source: EIA's Residential Energy Use Survey 2001

Table 13: Relationship between the Degree of County Sprawling, Size of County Population, and the UHI Intensity Measured by the Changes in Heating and Cooling Degree-Days – National model (non-mountainous regions) (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of the Reductions in Heating Degree-Days and the Increase in Cooling Degree-Day

	HDD			CDD		
	Coefficient	*t*	*p*	**Coefficient**	*T*	*p*
Ln (Sprawl Index)	1.159	2.4	0.017	1.051	2.2	0.030
Ln (Population)	0.082	1.2	0.244	0.054	0.8	0.437
Latitude	0.342	2.6	0.010	-0.050	2.6	<0.001
Longitude	-0.020	-5.1	<0.001	-0.007	-1.7	0.086
Topographic Feature						
Coast	-0.644	-3.3	0.001	-0.552	-3.1	0.002
Valley	-0.045	-0.3	0.739	-0.390	-2.9	0.004
R-Squared	0.1495			0.1139		
Number of Counties	543			543		

Data Source: County Sprawl Index (Ewing, Brownson et al. 2006), Kalnay and Cai (2003), and ESRI Data & Maps 2005 (ESRI 2005)

Table 14: Relationship between Size of County Area, Size of County Population, and the UHI Intensity Measured by the Changes in Heating and Cooling Degree-Days (with Coefficients, t-Ratios, and Significance Levels)

Dependent Variable: Natural Log of the Reductions in Heating Degree-Days and the Increase in Cooling Degree-Day

	HDD			*CDD*		
	Coefficient	*t*	*p*	**Coefficient**	*T*	*p*
Ln (Area)	-0.081	-0.9	0.391	-0.027	-0.3	0.783
Ln (Population)	0.209	4.0	<0.001	0.163	3.2	0.002
Latitude	0.036	2.7	0.008	-0.048	-3.4	0.001
Longitude	-0.022	-4.6	<0.001	-0.007	-1.6	0.123
Topographic Feature						
Coast	-0.528	-2.8	0.005	-0.457	-2.7	0.008
Valley	-0.057	-0.4	0.683	-0.403	-2.9	0.004
R-Squared	0.1385			0.1037		
Number of Counties	543			543		

Data Source: County Sprawl Index (Ewing, Brownson et al. 2006), Kalnay and Cai (2003), and ESRI Data & Maps 2005 (ESRI 2005)

Bibliography

1. Amato, A., M. Ruth, et al. (2005). "Regional Energy Demand Responses to Climate Change: Methodology and Application to the Commonwealth of Massachusetts." Climatic Change 71(1): 175 - 201.

2. Anderson, G. M. and M. K. Santore (2002). Our Built and Natural Environments: A Technical Review of the Interactions between Land Use, Transportation, and Environmental Quality, Collingdale: DIANE Publishing Company.

3. Anderson, W. P., P. S. Kanaroglou, et al. (1996). "Urban Form, Energy and the Environment: A Review of Issues, Evidence and Policy." Urban Studies 33(1): 7-35.

4. Attarian, J. (2002). "The Coming End of Cheap Oil." The Social Contract Summer: 276-286.

5. Bahree, B. (2006). Oil Settles Above $70 a Barrel, Despite Inventories at 8-Year High. The Wall Street Journal: A1.

6. Bakhtiari, A. M. S. (2004). "World oil production capacity model suggests output peak by 2006–07." Oil and Gas Journal Apr.: 18-20.

7. Balling, R. C., J. A. Skindlov, et al. (1990). "The impacts of increasing summer mean temperatures on extreme maximum and minimum temperature in Phoenix, Arizona." Journal of Climate 3: 1491-1494.

8. Barnett, J. and W. N. Adger (2003). "Climate Dangers and Atoll Countries." Climatic Change 61(3): 321 - 337.

9. Belzer DB, and KA Cort. (2004). Statistical Analysis of Historical State-Level Residential Energy Consumption Trends. In ACEEE Summer Study on Energy Efficiency in Buildings. PNNL-SA-41129, Pacific Northwest National Laboratory, Richland, WA.

10. Benfield, F. K., M. D. Raimi, et al. (1999). Once There Were Greenfield: How Urban Sprawl Is Undermining America's Environment, Economy and Social Fabric. New York, Natural Resources Defense Council.

11. Bentley, R. W. (2002). "Global Oil & Gas Depletion: An Overview." Energy Policy 30: 189–205.

12. Bento, A. M., M. L. Cropper, et al. (2003). The impact of urban spatial structure on travel demand in the United States, The World Bank.

13. Biirer, M. J., D. B. Goldstein, et al. (2004). Location Efficiency as the Missing Piece of The Energy Puzzle: How Smart Growth Can Unlock Trillion Dollar Consumer Cost Savings. 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy-Efficient Economy.

14. Blok, K. (2005). "Enhanced Policies for the Improvement of Electricity Efficiencies." Energy Policy 33: 1635-1641.

15. Bornstein, R. and Q. Lin (2000). "Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies." Atmospheric Environment 34(3): 507-516.

16. Brazdil, R. and M. Budikova (1999). "An urban bias in air temperature fluctuations at the Klementinum, Prague, the Czech Republic." Atmospheric Environment 33: 4211–4217.

17. Brian Stone, J. (2006). Physical planning and urban heat island formation: how cities change regional climate. Smart Growth and Climate Change: Regional Development, Infrastructure and Adaptation. M. Ruth. Cheltenham, UK and Northampton, MA, US, Edward Elgar.

18. Burchell, R. W. (1992). Impact Assessment of the New Jersey Interim State Development and Redevelopment Plan. Trenton, NJ, New Jersey Office of State Planning.

19. Burchell, R. W. and D. Listokin (1995). Development Patterns and Infrastructure Costs. Land, Infrastructure, Housing Costs, and Fiscal Impacts Associated with Growth: The Literature on the Impacts of Traditional versus Managed Growth. R. W. Burchell and D. Listokin. New Brunswick, NJ, Center for Urban Policy Research, Rutgers University: 9-20.

20. Burchell, R. W., D. Listokin, et al. (1998). The Costs of Sprawl -- Revisited. Washington DC, Transportation Research Board.

21. Burchell, R. W., G. Lowenstein, et al. (2002). Costs of Sprawl --- 2000. Washington DC, Transportation Research Board.

22. Burchell, R. W. and E. Schmeidler (1993). The Demographic and Social Difference Between Central Cities and Suburbs as They Relate to the Job

Fulfillment of Urban Residents. The National Conference on Metropolitan America in Transition: Implications for Land Use and Transportation Planning, Cambridge, MA, Lincoln Institute of Land Policy.

23. Census (2004). Public Use Microdata Sample Technical Documentation: 2000 Census of Population and Housing, U.S. Department of Commerce, Economics and Statistics Administration, U.S. CENSUS BUREAU.

24. Cervero, R. (1996). "Mixed land-uses and commuting: Evidence from the American Housing Survey." Transportation Research A 30(5): 361-377.

25. Changnon, S. A., K. E. Kunkel, et al. (1996). "Impacts and responses to the 1995 heat wave: A call to action." Bulletin of the American Meteorological Society 77: 1497-1506.

26. Cheshire, P. and S. Sheppard (1998). "Estimating the Demand for Housing, Land, and Neighborhood Characteristics." Oxford Bulletin of Economics and Statistics 60(3): 357-382.

27. Conte, C. R. (2000). "The Boys of Sprawl." Governing: 28-33.

28. Crane, R. (1996). "Cars and Drivers in the New Suburbs: Linking Access to Travel in Nontraditional Planning." American Planning Association 62(1): 51-67.

29. Crane, R. and R. Crepeau (1998). "Does neighborhood design influence travel? A behavior analysis of travel diary and GIS data." Transportation Research Part D: Transport and Environment 3: 225-238.

30. Crompton, P. and Y. Wu (2005). "Energy Consumption in China: Past Trends and Future Directions." Energy Economics 27: 195-208.

31. DOE (2005). "Retailed Gasoline Historical Price." from http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_history.html.

32. ECOTEC (1993). Reducing transport emissions through Sustainable development and planning. London, HMSO.

33. EIA (2000). Trends in Residential Air-Conditioning Usage from 1978 to 1997.

34. EIA (2003). "Electricity Transmission Fact Sheet." From http://www.eia.doe.gov/cneaf/electricity/page/fact_sheets/transmission.html

35. EIA. (2004a). Emissions of Greenhouse Gases in the United States 2003.

36. EIA (2004b). "2001 RECS Public Use Data Files." from
    http://www.eia.doe.gov/emeu/recs/recs2001/publicuse2001.html.

37. EIA (2005a). Annual Energy Review.

38. EIA (2005b). Annual Energy Review 2005.

39. EPA (2001). Our Built and Natural Environments: A Technical Review of the
    Interactions between Land Use, Transportation, and Environmental Quality.
    Washington, DC, United States Environmental Protection Agency.

40. EPRI (2002). R&D challenges in Security of the Electricity Infrastructure.
    Security, Privacy & Critical Infrastructure Protection: Seminar series at the
    University of California- Berkeley.

41. ESRI (2005). ESRI Data & Maps Media Kit.

42. Ewing, R. (1994). "Characteristics, Causes, and Effects of Sprawl: A Literature
    Review." Environmental and Urban Issues 21(2): 1-15.

43. Ewing, R. (1995). Beyond density, mode-choice, and single-purpose trips. The
    74th Annual Meeting of the Transportation Research Board, Washington DC.

44. Ewing, R. (1997). "Is Los Angeles-Style Sprawl Desirable?" Journal of the
    American Planning Association 63(1): 107-126.

45. Ewing, R., R. C. Brownson, et al. (2006). Relationship between Urban Sprawl and
    Weight of U. S. Youth., Working Paper

46. Ewing, R. and R. Cervero (2001). "Travel and the Built Environment: A
    synthesis." Transportation Research Record 1780: 87-114.

47. Ewing, R., R. Pendall, et al. (2002). Measuring Sprawl and Its Impacts.
    Washington, DC, Smart Growth America.

48. Ewing, R., R. A. Schieber, et al. (2003). "Urban Sprawl as a Risk Factor in Motor
    Vehicle Occupant and Pedestrian Fatalities." American Journal of Public Health
    93(9): 1541-1545.

49. Ewing, R., T. Schmid, et al. (2003). "Relationship between Urban Sprawl and Physical Activity, Obesity and Morbidity." the American Journal of Health Promotion 18(1).

50. Figuerola, P. and N. Mazzeo (1998). "Urban–rural temperature differences in Buenos Aires." International Journal of Climatology 18: 1709–1723.

51. Frank, J. E. (1989). The Costs of Alternative Development Patterns: A Review of the Literature. Washington, DC, Urban Land Institute.

52. Freeman, L. (2001). "The Effects of Sprawl on Neighborhood Social Ties: An Explanatory Analysis." Journal of the American Planning Association 67(1): 69-77.

53. Fulton, W., R. Pendall, et al. (2001). Who Sprawl most? How growth patterns differ across the U.S. Washington, DC, Brookings Institution.

54. Galster, G., R. Hanson, et al. (2001). "Wrestling sprawl to the ground: Defining and measuring an elusive concept." Housing Policy Debate 12(4): 681-717.

55. Gedzelman, S. D., S. Austin, et al. (2003). "Mesoscale aspects of the Urban Heat Island around New York City." Theoretical and Applied Climatology 75(1-2): 29 - 42.

56. Gerencher, K. (2006) "Bigger houses bring energy woes: Efficient materials, appliances have limited cost effects." MarketWatch, Mar 14, 2006

57. Glaeser, E. L. and M. E. Kahn (2003). "Sprawl and Urban Growth." Harvard Institute of Economic Research Discussion Paper, Number 2004.

58. Golany, G. (1996). "Urban design morphology and thermal performance." Atmospheric Environment 30(3): 455-465.

59. Gordon, P. and H. W. Richardson (1997). "Are Compact Cities a Desirable Planning Goal?" Journal of the American Planning Association 63(1): 95-106.

60. Greene, D. L. and J. L. Hopson (2003). Running Out of and Into Oil: Analyzing Global Depletion and Transition through 2050. Oak Ridge, Tennessee, Oak Ridge National Laboratory.

61. Greening, L., D. Green, et al. (2000). "Energy efficiency and consumption - the rebound effect - a survey." Energy Policy (28): 389-401.

62. Greenough, G., M. McGeehin, et al. (2001). "The Potential Impacts of Climate Variability and Change on Health Impacts of Extreme Weather Events in the United States." Environmental Health Perspectives 109.

63. Hadfield, P. (2000). "Totally tropical Tokyo." New Scientist 167: 10.

64. Harris, L. D. (1984). The Fragmented Forest. Island Biogeography Theory and the Preservation of Biotic Diversity. Chicago, IL, University of Chicago Press: 71-92.

65. Hayward, S. (1998). "Legends of the Sprawl." Policy Review 91: 26-32.

66. Hogan, A. and M. Ferrick (1998). "Observations in non-urban heat islands." Journal of Applied Meteorology 37: 232–236.

67. Holtzclaw, J., R. Clear, et al. (2002). "Location Efficiency: Neighborhood and Socioeconomic Characteristics Determine Auto Ownership and Use – Studies in Chicago, Los Angeles and San Francisco." Transportation Planning and Technology 25: 1-27.

68. IEA (2004). Electricity Information 2004, International Energy Agency.

69. IPCC, T. I. P. o. C. C. (1996). Climate Change 1995: The Science of Climate Change. Cambridge, Cambridge University Press.

70. Jager, J. (1983). Climate and Energy Systems: A Review of their Interactions. New York, NY, JohnWiley & Sons.

71. Jauregui, E. (1997). "Heat island development in Mexico City." Atmospheric Environment 31(22): 3821-3831.

72. Jr, J. L. H., P. J. Tharakan, et al. (2004). "Forecasting the limits to the availability and diversity of global conventional oil supply." Energy 29: 1673–1696.

73. Kahn, M. E. (2001). "Does Sprawl Reduce the Black/White Housing Consumption Gap?" Housing Policy Debate 12(1): 77-86.

74. Kain, J. F. (1992). "The Spatial Mismatch Hypothesis: Three Decades Later." Housing Policy Debate 3(1): 371-459.

75. Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K. C., Ropelewski C., Wang J., Leetmaa A., Reynolds R.,

Jenne R., Joseph D. (1996). "The NCEP/NCAR 40-year reanalysis project." Bulletin of American Meteorology Society 77: 437-471.

76. Kalnay, E. and M. Cai (2003). "Impact of urbanization and land-use change on climate." Nature 423: 528-531.

77. Katz, M. L. and H. S. Rosen (1998). Microeconomics. Boston, Irwin McGraw-Hill.

78. Kautz, R. S. (1993). "Trends in Florida's Wildlife Habitat 1936-1987." Florida Scientist 56: 7-24.

79. Kelly-Schwartz, A., J. Stockard, et al. (2005). "Is sprawl unhealthy? A multi-level analysis of the relationship of metropolitan sprawl to the health of individuals." Journal of Planning Education and Research In Press.

80. Kessler, J. and W. Schroeer (1995). "Meeting Mobility and Air Quality Goals: Strategies that Work." Transportation Planning and Technology 22(3): 241-272.

81. Kidder, S. and O. Essenwanger (1995). "The effect of clouds and wind on the difference in nocturnal cooling rates between urban and rural
82. areas." Journal of Applied Meteorology 34: 2440–2448.

83. Klysik, K. and K. Fortuniak (1999). "Temporal and spatial characteristics of the urban heat island of Lodz, Poland." Atmospheric Environment 33: 3885-3895.

84. Koomey, J. and R. E. Brown (2002). The Role of Building Technologies in Reducing and Controling Peak Electricity Demand. Berkeley, CA, Lawrence Berkeley National Laboratory.

85. Kunkle, R., L. Lutzenhiser, et al. (2004). New Imagery and Directions for Residential Sector Energy Policies. 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy-Efficient Economy.

86. Landis, J. D. (1995). "Imagining Land Use Futures: Applying the California Urban Futures Model." Journal of the American Planning Association 61(4): 438–457.

87. Landsberg, H. (1981). The urban climate, Academic Press. 28: 275.

88. Laurence, M. T. (2004). Changes in the Patterns of Energy Consumption and Expenditures over the Past Quarter Century. 2004 ACEEE Summer Study on

Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy-Efficient Economy.

89. Lebot, B., P. Bertoldi, et al. (2004). Consumption versus Efficiency: Have We Designed the Right Policies and Programmers? 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy-Efficient Economy.

90. Lightfoot, H. D. and C. Green (2001). Energy intensity decline implications for stabilization of atmospheric CO2 content, Centre for Climate and Global Change Research, McGill University.

91. Lopez, R. and H. P. Hynes (2003). "Sprawl In The 1990s: Measurement, Distribution, and Trends." Urban Affairs Review 38(3): 325-355.

92. Lowry, W. P. (1977). "Empirical estimation of urban effects on climate: a problem analysis." Journal of Applied Meteorology 16: 129.

93. Magee, N., J. Curtis, et al. (1999). "The urban heat island effect at Fairbanks, Alaska." THEORETICAL AND APPLIED CLIMATOLOGY 64(1-2): 39-47.

94. Malpezzi, S. and W.-K. Guo (2001). Measuring ''sprawl'': Alternative measures of urban form in U.S. metropolitan areas. Center for Urban Land Economics Research, University of Wisconsin, Madison.

95. McCann, B. A. and R. Ewing (2003). Measuring the Health Effects of Sprawl: A National Analysis of Physical Activity, Obesity and Chronic Disease, Smart Growth America, Surface Transportation Policy Project.

96. McMichael, A. J. (2000). "The urban environment and health in a world of increasing globalization: Issues for developing countries." Bulletin of the World Health Organization 78: 1117-1126.

97. Meyers, S., J. E. McMahon, et al. (2003). "Impacts of US federal energy efficiency standards for residential appliances." Energy 28: 755-767.

98. Miron, J. R. (2004). "Housing Demand, Coping Strategy, and Selection Bias." Growth and Change 35(2): 220-261.

99. Morris, C. and I. Simmonds (2000). "Associations between varying magnitudes of the urban heat island and the synoptic climatology in Melbourne, Australia." International Journal of Climatology 20(15): 1931-1954

100.	Morris, C., I. Simmonds, et al. (2001). "Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city." Journal of Applied Meteorology 40: 169–182.

101.	NASA (1999). "Atlanta's Urban Heat Island."

102.	Nelson, A. C., R. Pendall, et al. (2002). The Link between Growth Management and Housing Affordability: The Academic Evidence. Growth without Growth: An Alternative Economic Development Goal for Metropolitan Areas. Washington D.C., The Brookings Institution Center on Urban and Metropolitan Policy.

103.	Newman, P. W. and J. R. Kenworthy (1996). "The land use - transport connection: An overview." Land Use Policy 13(1): 1-22.

104.	Newman, P. W. G. and J. R. Kenworthy (1988). "The Transport Energy Trade-Off: Fuel-Efficient Traffic versus Fuel-Efficient Cities." Transportation Research A 22(3): 163-174.

105.	Oke, T. R. (1987). Boundary Layer Climates, Routledge.

106.	Oke, T. R., G. T. Johnson, et al. (1991). "Simulation of surface urban heat islands under "ideal" conditions at night. Part 2: Diagnosis of causation." Boundary-Layer Meteorology 56: 339–358.

107.	Park, H. (1986). "Features of the heat island in Seoul and its surrounding cities." Atmospheric Environment 20: 1859–1866.

108.	Perterson, T. C. (2003). "Assessment of Urban Versus Rural in Situ Surface Temperatures in the Contiguous United States." Journal of Climate 16(18): 2941-2959.

109.	Philandras, C., D. Metaxas, et al. (1999). "Climate variability and urbanization in Athens." Theoretical and Applied Climatology 63: 65–72.

110.	Pinho, O. and M. Orgaz (2000). "The urban heat island in a small city in coastal Portugal." INTERNATIONAL JOURNAL OF BIOMETEOROLOGY 44(4): 198-203.

111.	Plantinga, A. and S. Bernell (2005). The association between urban sprawl and obesity: is it a two-way street?

112.   Pon, B., D. M. Stamper-kurn, et al. (2000). Existing Climate Data Sources and Their Use in Heat Island Research, LBL.

113.   Popenoe, D. (1979). "Urban Sprawl - Some Neglected Sociological Considerations." Sociology and Social Research 63(2): 255-268.

114.   R. S. Means Company (2000). Residential Cost Data, 20th Annual Edition. Kingston, MA.

115.   Raudenbush, S. and A. Byrk (2002). Hierarchical Linear Models: Applications and Data Analysis Methods. Thousand Oaks, California, Sage Publications.

116.   Rosenfeld, A., H., S. Akbari, et al. (1995). "Mitigation of urban heat islands: Materials, utility programs, updates." Energy and Buildings 22(255-265).

117.   Rosenfeld, A. H., et al., (1995). "Mitigation of Urban Heat Islands-Materials, Utility Programs, Updated." Energy and Buildings, 22(3): 255-265.

118.   Rosenfeld, A. H. and J. J. Romm (1996). Policies to Reduce Heat Islands: Magnitudes of Benefits and Incentives to Achieve Them. Proceedings of the 1996 LBL-38679 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.

119.   Ruth, M. and A. Lin (2006). Regional energy demand and adaptations to climate change: methodology and application to the State of Maryland, US. Smart Growth and Climate Change: Regional Development, Infrastructure and Adaptation. M. Ruth. Cheltenham, UK and Northampton, MA, US, Edward Elgar.

120.   Ruth, M. and F. Rong (2006). Smart Growth and Climate Adaptation: Research Themes and Challenge. Smart Growth and Climate Change: Regional Development, Infrastructure and Adaptation. M. Ruth. Cheltenham, UK and Northampton, MA, US, Edward Elgar.

121.   Saelens, B. E., J. F. Sallis, et al. (2003). "Neighborhood-Based Differences in Physical Activity: An Environment Scale Evaluation." American Journal of Public Health 93(9).

122.   Sailor, D (1998). Energy-use implications of climate change. Working Report. National Institute for Global Environmental Change.

123. Sailor, D. J. and L. Lu. (2004). "A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas." Atmospheric Environment 38: 2737–2748.

124. Sailor, D. J. and J. R. Munoz (1997). "Sensitivity of electricity and natural gas consumption to climate in the USA - Methodology and results for eight states." Energy and Buildings 22(10): 987-998.

125. Santamouris, M., N. Papanikolaou, et al. (2000). Urban canyon experiments in Athens Part A: Temperature distribution, University of Athens.

126. Siderius, H.-P. (2004). The End of Energy Efficiency Improvement = The Start of Energy Savings? 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy-Efficient Economy.

127. Skaburskis, A. (1997). "Gender Differences in Housing Demand." Urban Studies 34(2): 275-320.

128. Snyder, K. and L. Bird (1998). Paying the Costs of Sprawl: Using Fair-Share Costing to Control Sprawl.

129. Solecki, W. and C. Rosenzweig (2003). The Urban Heat Island effect and Mitigation Strategies – Connections to sprawl.

130. Steinecke, K. (1999). "Urban climatological studies in the Reykjav ¡ä ik subarctic environment, Iceland." Atmospheric Environment 33: 4157–4162.

131. Stoll, M. A. (2005). Urban Sprawl and Racial Segregation. Twenty-Seventh Annual APPAM Research Conferences: Understanding and Informing Policy Design, Washington, DC.

132. Stone, B. and M. O. Rodgers (2001). "Urban form and thermal efficiency: how the design of cities influences the urban heat island effect." Journal of American Planning Association 67(2): 186-198.

133. STPP (1999). Aggressive Driving: Where You Live Matters, Surface Transportation Policy Project.

134. STPP (2003). Transportation Costs and the American Dream - Why a Lack of Transportation Choices Strains the Family Budget and Hinders Home ownership, Surface Transportation Policy Project.

135. Sturm, R. and D. Cohen (2004). "Suburban sprawl and physical and mental health." Public Health 118(7): 488-496.

136. Suresh, P. R. and S. Elachola (2000). Distribution losses of Electricity and Influence of Energy Flow: A Case Study of a Major Section in Kerala.

137. Taha, H. (1997). "Urban climates and heat islands: Albedo, evapotranspiration and anthropogenic heat." Energy and Buildings 25(99–103).

138. Taha, H., S. Douglas, et al. (1997). "Mesoscale meteorological and air quality impacts of increased urban albedo and vegetation." Energy and Buildings 25: 169-177.

139. Taha, H. and A. Meier (1997). Mitigation of Urban Heat Islands: Meteorology, Energy, and Air Quality Impacts. Proceedings of the International Symposium on Monitoring and Management of Urban Heat Island, Keio University, Fujisawa, Japan.

140. Torok, S., C. Morris, et al. (2001). "Urban heat island features of southeast Australian towns." Australian Meteorological Magazine 50(1): 1-13.

141. Trenberth, K. (2005). "Uncertainty in Hurricanes and Global Warming." Science 308: 1753-1754.

142. Unger, J., Z. Sumeghy, et al. (2001). "Temperature cross-section features in an urban area." Atmospheric Research 58(2).

143. United Nations (2004). WORLD URBANIZATION PROSPECTS: THE 2003 REVISION.

144. Unwin, D. (1980). "The synoptic climatology of Birmingham's heat island." Weather 35(43–50).

145. USA Today (2001). A comprehensive look at sprawl in America.

146. Voogt, J. A. (2004). "Urban Heat Islands: Hotter Cities." from http://www.actionbioscience.org/environment/voogt.html.

147. Wassmer, R. W. and M. C. Baass (2005). "Does a More Centralized Urban Form Raise Housing Prices?" Journal of Policy Analysis and Management Forthcoming.

148.	Wienert, U. and W. Kuttler (2005). "The dependence of the urban heat island intensity on latitude: A statistical approach." Meteorologische Zeitschrift 14(5): 677-686.

149.	Wolman, H., G. Galster, et al. (2005). "The Fundamental Challenge in Measuring Sprawl: Which Land Should Be Considered?" The Professional Geographer 57(1): 94-105.

150.	Wong, N., S. Tay, et al. (2003). "Life cycle cost analysis of rooftop gardens in Singapore." Building and Environment 383(3): 499-509.

151.	Yamashita, S., K. Sekine, et al. (1986). "On relationships between heat island and sky view factor in the cities of Tama River basin, Japan." Atmospheric Environment 20: 681–686.