The Impact of Urban Form on U.S. Residential Energy Use

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Abstract

While the impact of urban form on transportation energy use has been studied extensively, its impact on residential energy use has not. This article presents a conceptual framework linking urban form to residential energy use via three causal pathways: electric transmission and distribution losses, energy requirements of different housing stocks, and space heating and cooling requirements associated with urban heat islands. Two of the three can be analyzed with available national data.

After we control for other influences, residents of sprawling counties are more likely to live in single-family detached houses than otherwise comparable residents of compact counties and also more likely to live in big houses. Both lead to higher residential energy use. Because of the urban heat island effect, residents of sprawling counties across the nation on average pay a small residential energy penalty relative to residents of compact counties. Implications for urban planning are explored.

Keywords: Energy; Land use; Smart growth

Introduction

The balance between energy supply and demand is more fragile than ever because of the dwindling reserves of fossil fuels and increasing demand from India, China, and other developing countries that are embracing Western-style car culture. This imbalance is projected to have dire economic consequences when conventional oil production eventually peaks, as it must for this nonrenewable resource (Attarian 2002; Hallock et al. 2004). The International Energy Agency's (2007) optimistic forecast shows worldwide oil production continuing to rise (the dotted line in figure 1), while the sobering assessment of the Energy Watch Group (2007) suggests that oil production has already peaked (the curves in figure 1). Most forecasts lie between these two extremes, with peak production of conventional oil occurring between now and 2020 (Hirsch, Bezdek, and Wendling 2005). Although oil substitutes such as liquefied coal, oil shale, and tar sands will fill some of the gap, they are more expensive and environmentally damaging than conventional oil.

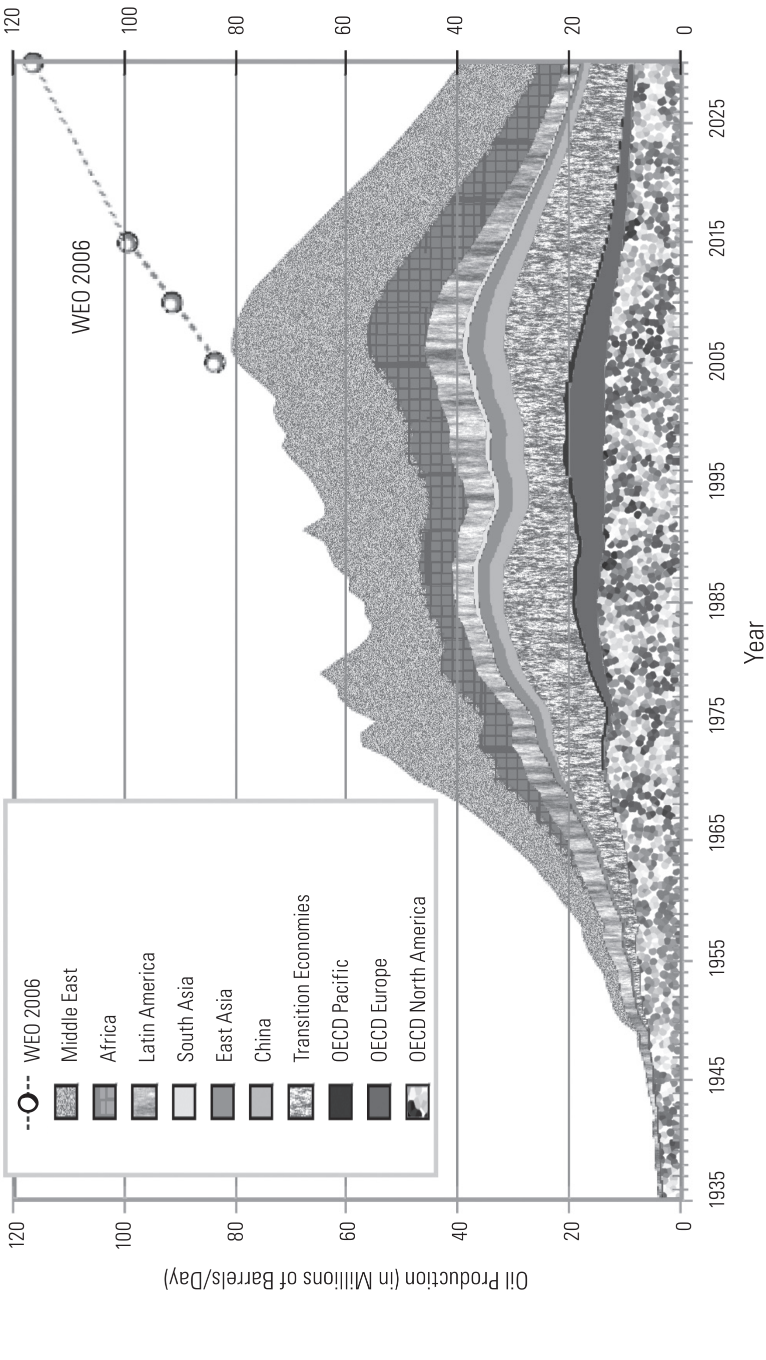
In a related matter, there is now a scientific consensus that the earth's climate is changing because of fossil fuel consumption (Barnett and Adger 2003; Greenough et al. 2001; Hegerl et al. 2007; Intergovernmental Panel on Climate Change 2007). Average global temperature is projected to rise between 1.1°C and 6.4°C within this century, with a best estimate of between 1.8°C and 4.0°C (see figure 2). With an increase of 3°C, more than one-third of all species will risk extinction. Between 2°C and 3°C, coastal flooding threatens to harm or displace 70 million to 250 million people, and hundreds of millions face an increased risk of hunger. From 1°C to 4°C, a partial deglaciation of the Greenland Ice Sheet will occur, meaning that sea level is destined to rise by four to six meters over centuries to millennia. Many of the effects of climate change, such as the shrinking sea ice in the Arctic and a prolonged drought in East Africa, are already evident. Closer to home, climate change is producing greater hurricane intensity in the North Atlantic, larger and more frequent wildfires in the western United States, and a greater number of extreme rainstorms or snowstorms in various part of the country (Emanuel 2005; Höppe and Pielke 2006; Madsen and Figdor 2007; Trenberth 2005; Westerling et al. 2006).

Within this larger picture, the importance of U.S. residential energy consumption becomes clear. In 2006, the U.S. residential sector consumed more than 21 quadrillion British thermal units (BTUs) of energy, accounting for more than one-fifth of total U.S. energy use (Energy Information Administration [EIA] 2007). This sector also produced more than one-fifth of total energy-related carbon dioxide emissions, approximately 1,254 million metric tons per year (EIA 2007).

Supply and demand sides

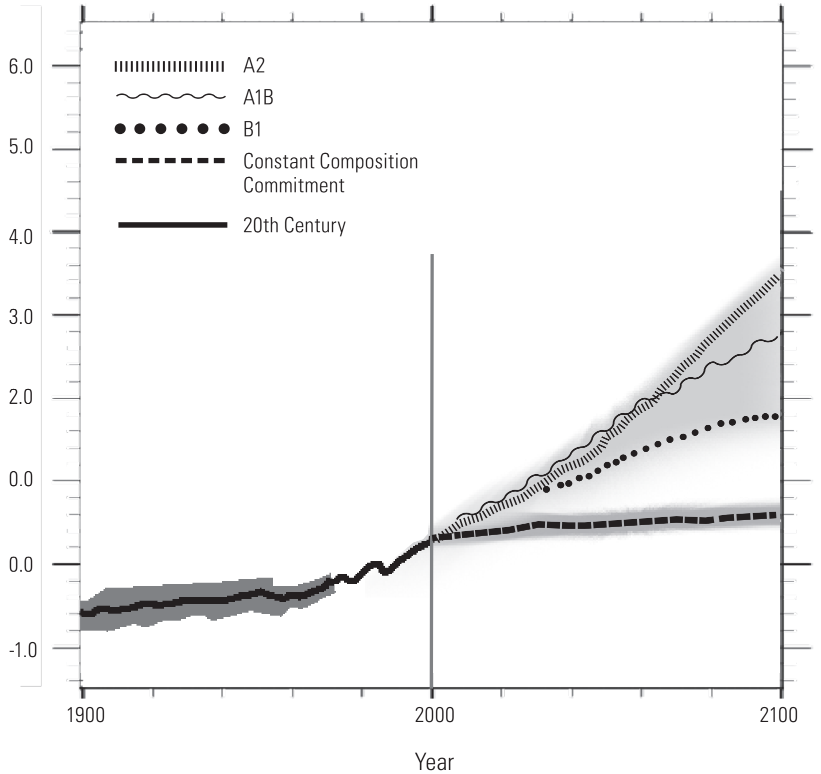
The United States has relied almost exclusively on technological advances to address the problem of limited supplies of energy and constantly increasing demands (Ewing et al. 2008; Siderius 2004). However, increasing energy efficiency through technological innovation just means more service per fixed amount of energy delivered. Despite increasing energy efficiency, per capita primary energy use in residential buildings has been gradually increas-

Figure 1. World Oil Production: Best- and Worst-Case Scenarios



Source: Energy Watch Group (2007).
OECD = Organisation for Economic Co-operation and Development; WEO = *World Energy Outlook* (a publication of the International Energy Agency).

Figure 2. Average Global Surface Temperature Warming under Different Scenarios

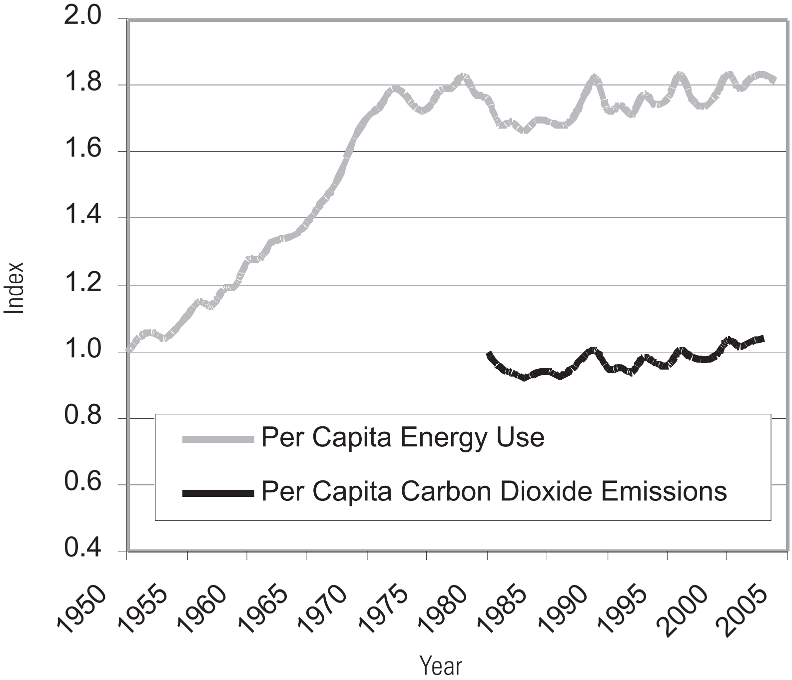


Source: Intergovernmental Panel on Climate Change 2007.
Note: The curves represent different future emissions scenarios developed by the Intergovernmental Panel on Climate Change. The A2 emissions scenario assumes a very heterogeneous world with high population growth, slow economic development, and slow technological change. The A1B scenario assumes a world of very rapid economic growth, a global population that peaks in mid-century, rapid introduction of new and more efficient technologies, and balanced energy sources. B1 assumes a conservation-oriented and relatively homogenous world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. Constant composition commitment refers to constant concentrations of greenhouse gases at year 2000 levels.

ing since the early 1980s, albeit at a slower rate than in the early 1950s to late 1970s, and per capita residential emissions of carbon dioxide have consequently been increasing as well (see figure 3).

It is likely that per capita energy use and associated greenhouse gas emissions will continue to rise and that advances in technology alone will not achieve sustainable growth in energy use (Ewing et al. 2008; Kunkle et al. 2004; Lebot, Bertoldi, and Harrington 2004; Siderius 2004). Hence, demand-side measures will be required to keep supply and demand in reasonable balance.

Figure 3. Per Capita Energy Use and Per Capita Carbon Dioxide Emissions in the U.S. Residential Sector, 1950 to 2004



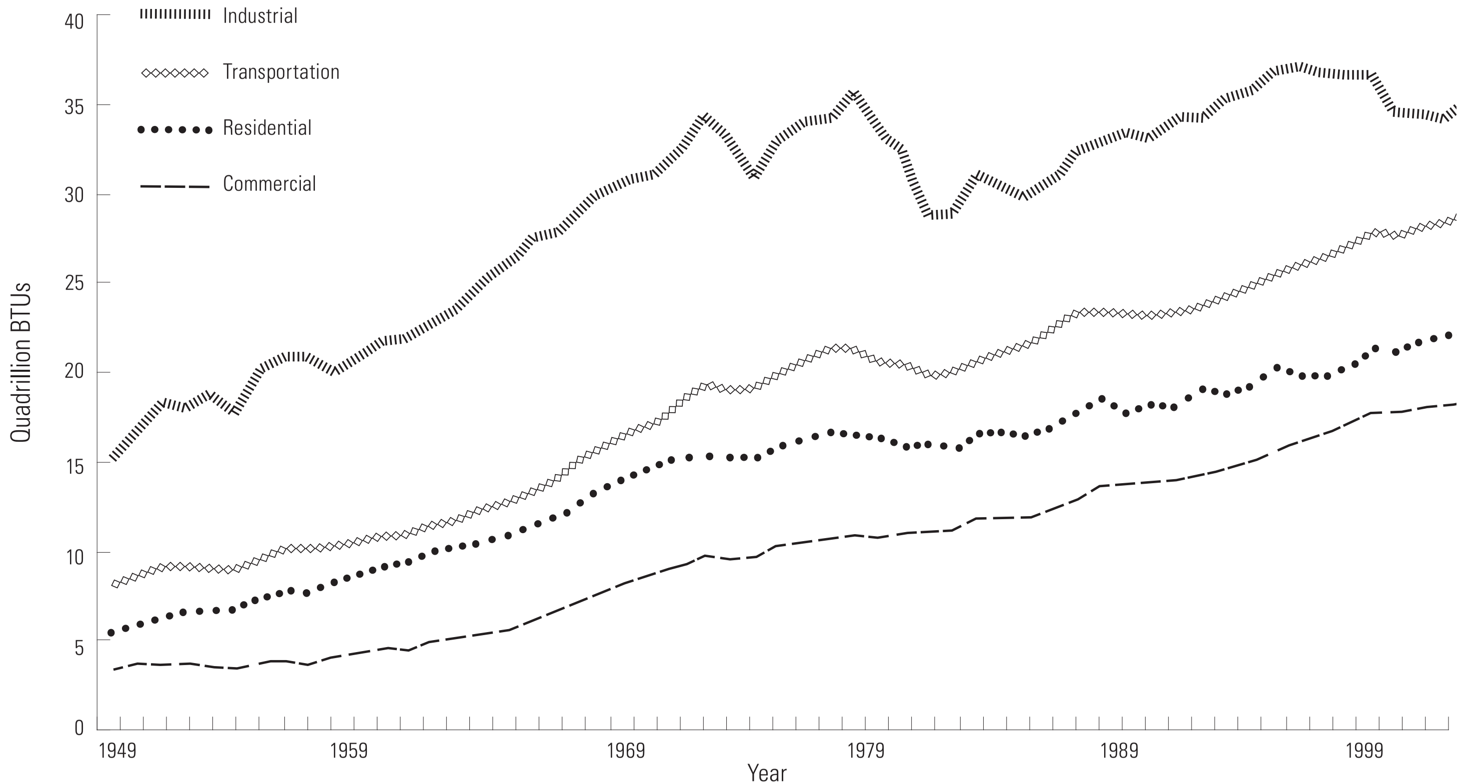
Source: EIA 2005.

Transportation and residential sectors

When it comes to urban energy use and related emissions, the transportation sector has gotten all of the attention (Bento et al. 2003; Burchell et al. 1998; Frank and Engelke 2005; Frank et al. 2006; Kessler and Schroeder 1995; Stone 2007; Stone et al. 2007; U.S. Environmental Protection Agency 2003). This focus is understandable, given the transportation sector's reliance on oil as a source of energy. The geopolitics of oil make headlines, but energy use by the U.S. residential sector is also a significant long-term threat to the planet. This sector consumes nearly as much energy as the transportation sector and produces nearly as much greenhouse gas emissions (see figure 4).

As climate change and energy security become defining issues for the urban planning profession, planners will be looking for strategies to reduce residential energy consumption. This article attempts to fill a gap in the

Figure 4. Total U.S. Energy Consumption by End-Use Sector, 1949 to 2006



Source: EIA 2007.

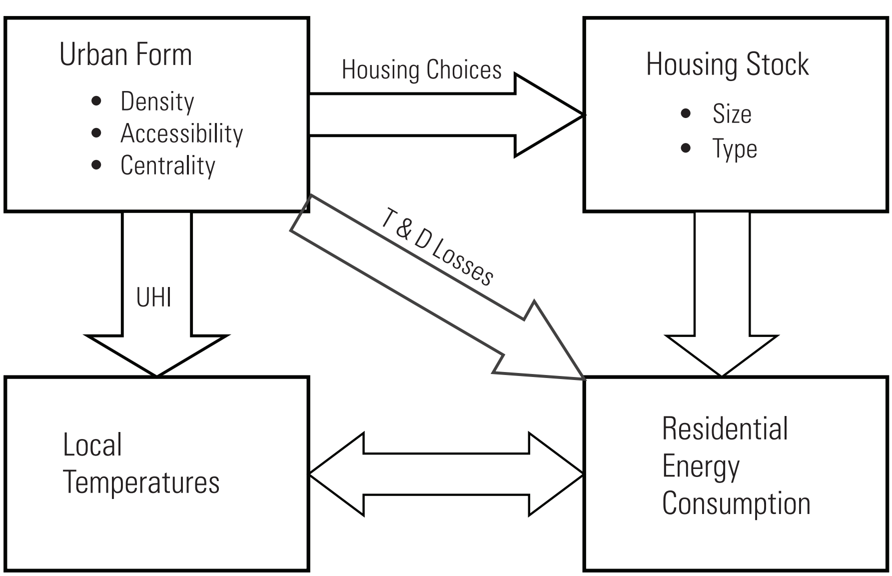
research literature by laying out a conceptual framework that relates urban form to residential energy use, describing the data and methods used to study these relationships and reporting the results of our statistical analyses. The article concludes with a discussion of the policy implications and limitations of this study. From our results, it appears that compact development, long promoted by planners for a host of other reasons, can help with these new challenges.

Conceptual framework

Our conceptual framework is shown in figure 5. Urban form can affect residential energy use through three causal pathways. The first is directly through electric transmission and distribution losses (T&D), the second is indirectly through the housing stock, and the third is indirectly through the formation of urban heat islands (UHIs).

Because the necessary data are available, this article focuses on the two indirect paths. The direct effect of urban form is likely to be small, because electric T&D losses account for less than 7 percent of the total electricity generated in the United States (EIA 2007).

Figure 5. Causal Paths between Urban Form and Residential Energy Consumption



Relevant literature

The effect of urban form on residential energy consumption is a new area of inquiry. Kahn (2000) used data from the 1993 U.S. Residential Energy Use Survey to study the impact of suburbanization on residential energy use. His research showed no significant difference between suburbanites and their counterparts in the central cities of the same metropolitan areas. However, his study did not operationalize urban form in a meaningful way, the distinction between urban and suburban being a gross one (Ewing 1997; Ewing, Pendall, and Chen 2002). Moreover, Kahn's (2000) research did not explore the causal pathways by which development patterns might influence residential energy use.

Residential energy use, housing stock, and urban form

Increasing residential energy use is linked to trends in housing consumption. Bigger houses require more energy than smaller ones because there is more space to heat and cool, and detached houses require more energy than attached houses of the same size because there is more exposed surface area. Over the past 30 years, the median floor area of new houses has increased by almost 50 percent. According to the National Association of Home Builders, new houses averaged 2,433 square feet in 2005, up from 2,095 square feet in 1995. The share of detached houses rose from 60 percent in 1995 to 62 percent in 2005, as determined by the American Housing Survey (AHS) (U.S. Bureau of the Census 1996, 2006).

Many factors have contributed to these trends. Previous studies have shown that housing consumption depends on such household characteristics as income, number of members, and ethnic background (Miron 2004; Skaburskis 1997).

Urban form may be a factor as well. The impact of urban form on the choice of house type and size is complex. Housing consumption is constrained by market conditions such as the availability and cost of residential land, construction costs, and other metropolitan area–specific characteristics (Cheshire and Sheppard 1998; Wassmer and Baass 2006). On the supply side, constrained land supplies and higher land prices, often found in compact areas, may favor multifamily and single-family attached housing so as to conserve on an expensive factor of production (Nelson et al. 2002). Or higher land prices may simply lead to larger houses on smaller lots, building up rather than out (Staley and Mildner 1999). On the demand side, because of higher prices (Glaeser and Kahn 2003), households in compact areas may have less disposable income and thus reduce the quantity of housing they demand (this is an "income effect," as described by Katz and Rosen 1998). Or they may consume more housing because they have more money to spend, thanks to lower transportation costs (Surface Transportation Policy Project 2003) (this is a "substitution effect," as described by Katz and Rosen 1998). The net impact of urban form on people's demand for housing is ambiguous and calls for empirical analysis.

Residential energy use, UHIs, and urban form

The UHI effect has multiple causes. Roads, buildings, and other constructed surfaces mostly absorb, rather than reflect, the sun's radiation. The displacement of trees, shrubs, and groundcover eliminates the natural cooling effects of shading and evapotranspiration. Urban activities such as motor vehicle travel and space heating and cooling produce waste heat. The resulting UHI effect is estimated to raise air temperature in a typical city by 1°C to 3°C relative to the surrounding rural area (Rosenfeld et al. 1995). The larger and denser a city, the greater the urban-rural difference in temperature (Hogan and Ferrick 1998; Park 1986; Torok et al. 2001). Because of the UHI effect, the energy demand for summertime cooling will be higher than it would be otherwise, while the demand for wintertime heating will be lower.

Development patterns affect the formation of UHIs in complex ways. Sprawling urban areas have less concentrated heat sources but also have more motor vehicle travel and resulting higher fossil fuel combustion (Bento et al. 2003; Burchell et al. 1998; Ewing, Pendall, and Chen 2002; Kessler and Schroeder 1995). Large-lot housing has more pervious surface and tree canopy than small-lot housing, but also has more impervious surface and uncanopied area because of larger houses, longer driveways, and bigger yards. It is not clear whether large- or small-lot housing generates more radiant heat per unit. "On average, each ¼- acre increase in parcel area was found to be associated with an increase in net thermal emissions of 33%. This finding directly challenges the common assumption that higher residential densities are less thermally efficient than lower residential densities" (Stone and Rodgers 2001, 194). Like the impact on housing stock, the impact of urban form on the formation of UHIs is ambiguous and calls for empirical analysis.

Methodology

Ideally, after controlling for other influences, we would have related urban form directly to the residential energy use of individual households and then decomposed urban effects according to our conceptual model. This would have required a large database of households, residential energy consumption values, many household covariates, and local geocodes for places of residence. Alas, no national source of residential energy data meets these requirements, so we used what we had—several national databases—to link urban form to residential energy consumption.

Our analytical structure consisted of six models, estimated with different data sets but linked conceptually through common variables as in figure 5. Descriptive statistics for these variables are presented in table 1.

1. *Residential energy models:* In these three models, the dependent variables are household energy consumption in each of three categories—space heating, space cooling, and all other uses—and the independent variables are house type, house size, urban temperature, and controls. Data are from the U.S. Residential Energy Consumption Survey (RECS) (EIA 2004).

2. *House type model:* In this model, the dependent variable is house type, and the independent variables are urban form and controls. Data are from the Public Use Microdata Sample (PUMS) (U.S. Bureau of the Census 2004).

3. *House size model:* In this model, the dependent variable is house size, and the independent variables are urban form and controls. Data are from the AHS (U.S. Bureau of the Census 1998, 2002).

4. *Urban temperature model:* In this model, the dependent variable is urban temperature, and the independent variables are urban form and controls.

So with this set of linked models, we related urban form to residential energy use indirectly through house type, house size, and urban temperature.

Data and measures

Urban form

It is no simple task to operationally define and objectively measure urban form. Several researchers (Burchfield et al. 2005; Fulton et al. 2001; Lopez and Hynes 2003; Malpezzi and Guo 2001) have created urban sprawl measures that focused on density. A few studies have measured sprawl in multidimensional ways. Galster et al. (2001) and Wolman et al. (2005), for example, defined sprawl as a land use pattern with low levels of density, continuity, concentration, compactness, centrality, nuclearity, diversity, and/or proximity.

Table 1. Descriptive Statistics for Variables

	2001 RECS	2000 Census	1998 and 2002 AHS
Household Variables	Mean (SD)	Mean (SD)	Mean (SD)
Primary energy use per household (in thousands of BTUs)	95,415 (58,093)	NA	NA
House size (square feet)	2,097 (1,410)	NA	1,689 (1,098)
House type			
Single family detached	60.5%	60.7%	65.5%
Single family attached	10.4%	7.6%	12.4%
Multifamily	29.1%	31.7%	22.1%
Year built			
1939 or earlier	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%
Household composition			
Number of children	0.51 (0.93)	0.71 (1.11)	0.71 (1.10)
Number of adults	2.11 (1.07)	1.95 (0.91)	1.92 (0.83)
Household income			
Less than $30,000	38.7%	30.5%	28.4%
$30,000 to $49,999	24.7%	21.5%	20.8%
$50,000 to $74,999	20.7%	19.8%	19.4%
$75,000 or more	15.9%	28.2%	31.4%
Race/Ethnicity of the householder			
White	70.7%	69.0%	71.3%
Black	12.8%	12.7%	10.4%
Hispanic	10.9%	12.3%	11.5%
Asian	3.5%	4.1%	5.2%
Other	2.1%	1.9%	1.6%
County variables			
County sprawl index	NA	107 (28)	110 (21)
Residential construction costs	NA	0.982 (0.145)	0.992 (0.130)
Total population in the MSAs	NA	4,388,905 (5,696,873)	4,048,688 (4,136,994)

Source: EIA (2004), Ewing et al. (2003), and U.S. Bureau of the Census (1998, 2002, 2004).
MSA = metropolitan statistical area; NA = not applicable; SD = standard deviation.

For this study, we needed broad coverage of the United States and geographic units of analysis that are large enough to capture determinants of an area's housing stock, yet small enough to be homogeneous with respect to climate. Ewing et al. (2003) estimated sprawl indices for 83 U.S. metropolitan areas and 448 counties in 1990 and 2000. Their indices have been widely used in sprawl-related research and have been validated in terms of expected outcomes (Cho et al. 2006; Doyle et al. 2006; Ewing, Brownson, and Berrigan 2006; Ewing et al. 2003; Ewing, Schieber, and Zegeer 2003; Joshu et al. 2008; Kahn 2006; Kelly-Schwartz et al. 2004; Plantinga and Bernell 2007; Stone 2007; Sturm and Cohen 2004).

We employed Ewing et al.'s (2003) county sprawl index as our measure of urban form. The index incorporates six variables from the U.S. Census and the U.S. Department of Agriculture's National Resources Inventory to account for residential density, street accessibility, and clustering of development:

1. Gross population density (persons per square mile)
2. Percentage of the county population living at low suburban densities (less than 1,500 persons per square mile)
3. Percentage of the county population living at moderate or high urban densities (more than 12,500 persons per square mile)
4. Population density in urban areas (persons per developed square mile)
5. Average block size (in square miles)
6. Percentage of blocks with areas of less than 1/100 of a square mile (the size of a typical traditional urban block)

These six variables were combined via principal components analysis into one factor that represents the degree of sprawl within the county. That factor was normalized such that the mean value for the 448 counties is 100, and the standard deviation is 25. The higher the value of the index, the more compact the county, and the smaller the value of the index, the more sprawling the county.[1] At the very compact end of the scale are four New York City boroughs, Manhattan, Brooklyn, the Bronx, and Queens; San Francisco

[1]It has been suggested more than once that the values of the sprawl index should be flipped, so that larger values correspond to greater degrees of sprawl. The original rationale for the positive scale had to do with subindices created to represent density, street accessibility, and other dimensions of sprawl. For them, larger values logically equated to less sprawl. A combined sprawl index assumed the same form. It seems to be too late to rescale the index now, since much has been published by us and by others using it in its current form. Almost all earlier research would show one relationship to the index, and this and later studies would show another. We wish we could go back to 2003 and do it differently. One researcher, Stone (2007), has recently done so.

County; Hudson County (Jersey City, NJ); Philadelphia County; and Suffolk County (Boston). At the very sprawling end of the scale are outlying counties of metropolitan areas in the Southeast and Midwest, such as Goochland County in the Richmond (VA) metropolitan area and Geauga County in the Cleveland metropolitan area. The index is positively skewed, with most counties clustering around intermediate levels of sprawl but with a few such as New York and San Francisco having very high densities and very high index values.

Residential energy use

The basic unit of analysis in this study is the individual household. Household energy data came from the RECS for 2001, the most recent year available. The RECS is a nonrandom national sample survey that provides energy data along with household and housing data. It was first conducted in 1978 and, since 1990, has been conducted about every four years. It provides total annual energy consumed and total annual expenditures by household for each major energy source—natural gas, electricity, fuel oil, kerosene, and liquefied petroleum gas (EIA 2004). It also provides end-use estimates of annual expenditures for space heating and cooling, water heating, general appliances, and other uses.

RECS 2001 surveyed 4,822 housing units from 50 states and the District of Columbia (EIA 2004). Because this study focused on metropolitan counties, housing units in rural areas were excluded. Mobile homes have also been excluded because of the small sample surveyed. Our final sample consisted of 3,737 housing units from cities, towns, and suburbs. Table 1 contains descriptive statistics for variables used in the residential energy consumption model.

Housing stock

Data limitations required that different data sources (and household samples) be used to derive the multiple relationships in our conceptual framework. To relate urban form to house type, we used the 2000 PUMS (U.S. Bureau of the Census 2004). For confidentiality reasons, the PUMS does not identify county of residence for counties with a population of less than 100,000, so our final PUMS sample consisted of 2,519,726 households from 266 metropolitan counties. Table 1 provides descriptive statistics for variables used in the house type model.

To relate urban form to house size, we used data from the AHS (U.S. Bureau of the Census 1998, 2002), which collects more detailed information on housing units (such as floor area) than the PUMS does. The AHS is both a national household survey where households are identified by metropolitan area and state and a set of metropolitan-area household surveys where households are identified by county. Metropolitan household surveys are conducted on a rotating basis in even-numbered years, with 47 metropolitan areas surveyed over 6 years. To increase the statistical power of the analysis and match 2000 county sprawl indices, 1998 and 2002 metropolitan area surveys were pooled. For confidentiality reasons, the AHS combines small counties with populations of less than 100,000. Our final AHS sample consisted of 61,947 households from 59 metropolitan counties. Descriptive statistics for variables used in the house size model are provided in table 1.

Because the RECS, PUMS, and AHS cover different geography, housing characteristics differ somewhat across our samples. The average house size from the AHS, for example, is about 1,700 square feet, while the average from the RECS is approximately 2,100 square feet. The integration of results later in the article is subject to the caveat that they are based on three different sampling frames.

Temperature/Climate

We used two different temperature sources for two different purposes. One was annual heating degree-days (HDDs) and cooling degree-days (CDDs) for households at their places of residence from the RECS, which was used to examine the dependence of space-conditioning energy use on HDDs and CDDs.[2] The other was degree-day data from Kalnay and Cai (2003), including observed surface degree-day data from weather stations and corresponding interpolated data from the gridded National Center for Environmental Prediction–National Center for Atmospheric Research 50-year Reanalysis (NNR). Because NNR degree-day data are insensitive to urbanization, the difference between these two is a measure of the intensity of the UHI effect. (For more details, see Kalnay and Cai 2003.)

[2]HDDs and CDDs are quantitative indices reflecting demand for energy to heat or cool houses and businesses. They are based on how far the daily average temperature departs from a human comfort level of 65°F. Simply put, each degree of temperature above 65°F counts as one CDD, and each degree below 65°F counts as one HDD. For example, a day with an average temperature of 80°F contributes 15 CDDs to the annual total.

Other data

Other data sources used in this study included the 2000 index of metropolitan residential construction cost from R. S. Means Company and geographic spatial data from Environmental Systems Research Institute (ESRI) Data & Maps (2005). The latter were tapped for county-specific characteristics such as population and land area, as well the ESRI County Boundary file to combine temperature data from Kalnay and Cai (2003). Such county-specific topographic features as coast, plain, and valley were derived from ESRI Data & Maps' (2005) North America Digital Elevation Model. Counties with plain as their dominant topographic feature have more than 75 percent of the land area located less than 250 meters above sea level, and counties with valley as their dominant topographic feature have more than 75 percent of the land area located more than 250 meters above sea level.

Analysis

Housing stock, temperature, and energy use

Ordinary least squares (OLS) regression analysis was used to examine the effects of individual household characteristics, housing unit characteristics, and ambient temperatures on household energy use. Models were estimated separately for three end uses—space heating, space cooling, and all other uses. To better fit the nonlinear relationship between energy use and the independent variables, we took the natural log of total delivered energy use per household per year. Energy use was regressed on the number of people in the household, annual income, race/ethnicity, the type of house (single family detached, single family attached, or multifamily), its size, the year it was constructed, climate (HDDs and CDDs), and composite energy price. Our residential energy use models are presented in table 2. In these models and all other models in this article, data were weighted to account for different probabilities of sample selection and survey response.

Urban form and housing stock

Hierarchical modeling was used to analyze relationships between urban form and housing stock. Hierarchical models have multiple levels, corresponding to the underlying data structure. Each level is nested within the level above it. In this case, households are nested within places. We could not use OLS regression to explain household outcomes in terms of place char-

Table 2. Relationship between Delivered Residential Energy Use in the United States, House Size and Type, and Other Control Variables (with Coefficients, *t*-Ratios, and Significance Levels)

	Heating		Cooling		Others	
	Coefficient	*p*-Value	Coefficient	*p*-Value	Coefficient	*p*-Value
House size (square feet)	0.00015	< 0.001	0.00012	< 0.001	0.00006	< 0.001
House type						
Mobile home	0.086	0.020	0.060	0.185	–0.025	0.333
Single family attached	–0.037	0.243	–0.115	0.008	–0.106	< 0.001
Multifamily	–0.431	< 0.001	–0.230	< 0.001	–0.366	< 0.001
Year built						
1940 to 1959	–0.194	< 0.001	–0.032	0.353	0.033	0.107
1960 to 1979	–0.355	< 0.001	–0.025	0.465	0.036	0.064
1980 to 2000	–0.456	< 0.001	–0.049	0.157	0.044	0.037
Household income						
$30,000 to $49,999	0.017	0.491	0.043	0.147	0.080	< 0.001
$50,000 to $74,999	0.021	0.450	0.131	< 0.001	0.131	< 0.001
$75,000 or more	0.142	< 0.001	0.169	< 0.001	0.233	< 0.001
Race/Ethnicity of the householder						
Black	0.283	< 0.001	0.166	< 0.001	0.117	< 0.001
Hispanic	–0.117	0.002	–0.230	< 0.001	–0.078	0.001
Asian	–0.162	0.003	–0.350	< 0.001	–0.225	< 0.001
Other	–0.007	0.918	–0.117	0.161	–0.149	0.001
Household composition						
Number of children	0.016	0.449	0.137	< 0.001	0.285	< 0.001
Number of adults	–0.002	0.916	0.210	< 0.001	0.184	< 0.001
Ln (energy price) ($ per thousand BTUs)	–1.006	< 0.001	–0.571	< 0.001	–0.403	< 0.001
HDDs	0.00020	< 0.001	NA	NA	NA	NA
CDDs	NA	NA	0.00054	< 0.001	NA	NA
R^2	0.7293		0.7072		0.5531	
Number of households	4,666		3,464		4,822	

Source: EIA (2004).
Notes: Dependent variables are the Lns of delivered residential energy use for heating, cooling, and other uses per household per year (in thousands of BTUs). Reference dummies included single-family detached housing, houses built before 1940, households with an annual income of less than $30,000, and white householders. Other controls for heating/cooling energy use models were the age of the heating/cooling equipment variable (dummies as less or more than 10 years old), the programmability of the thermostat of the heating/cooling equipment variable (dummies as yes or no), and the building insulation variable (dummies as well or poorly insulated), plus whether the cooling equipment was central or not and whether there was someone at home all day on a typical weekday (dummies as yes or no).
Ln = natural log; NA = not applicable.

acteristics since households in a given place share the characteristics of that place, thus violating the independence assumption of OLS regression. OLS standard errors of regression coefficients would therefore be underestimated for place characteristics. Moreover, OLS estimates of regression coefficients would be inefficient. Hierarchical modeling overcomes these limitations, accounting for the dependence among households residing in a given place and producing more accurate estimates of regression coefficients and standard errors (Raudenbush and Byrk 2002).

Within a hierarchical model, each level in the data structure is represented by its own submodel, which captures the structural relations and residual variability at that level. A Level 1 submodel explains household outcomes in terms of household characteristics for each place separately. A Level 2 submodel explains variations in Level 1 intercepts and slopes across places in terms of place characteristics. To model such complex data structures, we relied on HLM 6 (Hierarchical Linear and Nonlinear Modeling) software from Scientific Software International, Inc.

A hierarchical nonlinear model was estimated for the trichotomous outcome, house type (see table 3). The model is nonlinear because the dependent variable assumes only discrete values, not continuous ones. The model is trichotomous because dependent variables may assume three values—one for single family attached, a second for multifamily, and a third for the reference category, single family detached. The natural logarithm of the odds of choosing single-family attached or multifamily housing was regressed on individual household characteristics in the Level 1 model. Independent variables included the number of people in the household, annual income, and race/ethnicity. The intercepts and coefficients of Level 1 models were then regressed on place characteristics in the Level 2 model, specifically on the county sprawl index, the residential construction cost index, and the total population of the metropolitan area. All models included random effects.

A hierarchical linear model was estimated for the continuous outcome, house size (see table 4). The natural log of house size was regressed on individual household and housing characteristics in Level 1 models. The intercepts and coefficients of Level 1 models were then regressed on county-specific characteristics in Level 2 models. All models included random effects.

For both house type and house size models, we initially allowed only the intercept terms to vary as functions of place characteristics, plus random residuals. The resulting models are sometimes referred to as “random intercept” models. Then we relaxed the assumption of fixed coefficients and also modeled coefficients as functions of place characteristics, plus ran-

Table 3. Relationship between House Type, Urban Sprawl, and Control Variables in the United States (with Coefficients, *t*-Ratios, and Significance Levels)

	Single-Family Attached Housing			Multifamily Housing		
	Coefficient	*t*-Ratio	*p*-Value	Coefficient	*t*-Ratio	*p*-Value
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
Household composition						
Number of children	–0.203	–8.4	< 0.001	–0.357	–21.9	< 0.001
Number of adults	–0.698	–17.2	< 0.001	–1.124	–32.4	< 0.001
Household income						
$30,000 to $49,999	–0.106	–6.6	< 0.001	–0.466	–29.6	< 0.001
$50,000 to $74,999	–0.372	–13.6	< 0.001	–1.015	–36.7	< 0.001
$75,000 or more	–0.874	–28.8	< 0.001	–1.791	–35.6	< 0.001
Race/Ethnicity of the 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
Other	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 costs)	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			2,519,726			
Number of counties			266			

Source: Ewing et al. (2003), R. S. Means (2000), and U.S. Bureau of the Census (2004).
Notes: The dependent variable is the Ln of the odds that residents will live in different types of housing, and the reference category is single-family detached housing. Reference dummies included houses built before 1940, households with an annual income of less than $30,000, and white householders. Other controls included the square term of number of adults and children in the household. Regression results were estimations of fixed effects with robust standard errors.
Ln = natural log.

domly varying residuals, thereby capturing interactions between place and household characteristics. These are sometimes referred to as “random coefficient” models. The interactions among household and place characteristics were never significant in the house size model and seldom significant in the house type model. Therefore, only the random intercept forms of models are reported in tables 3 and 4.

Table 4. Relationship between House Size, Urban Sprawl, and Control Variables in the United States (with Coefficients, *t*-Ratios, and Significance Levels)

	Coefficient	*t*-Ratio	*p*-Value
House type			
Single family attached	−0.474	−23.5	< 0.001
Multifamily	−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
Household composition			
Number of children	0.010	2.5	0.013
Number of adults	0.121	12.1	< 0.001
Household income			
$30,000 to $49,999	0.074	7.1	< 0.001
$50,000 to $74,999	0.144	11.0	< 0.001
$75,000 or more	0.297	19.1	< 0.001
Race/Ethnicity of the householder			
Black	−0.095	−3.7	< 0.001
Hispanic	−0.135	−9.7	< 0.001
Asian	−0.034	−2.8	0.006
Other	−0.071	−4.5	< 0.001
County variables			
Ln (county sprawl index)	−0.402	−2.0	0.046
Ln (residential construction costs)	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 (place level)		59	

Sources: Ewing et al. (2003), R. S. Means (2000), and U.S. Bureau of the Census (1998, 2002).
Notes: The dependent variable is the Ln of square feet of housing units. Reference dummies included houses built before 1940, households with an annual income of less than $30,000, and white householders.
Other controls included the year 2002 dummy variable and the square terms of the number of adults and children in the household.
Ln = natural log.

Urban form and temperatures

OLS regression models and aggregate county-level data were used to examine the relationship between urban form and temperatures. The natural logs of observed HDDs and CDDs were each regressed on topographic dummy variables and the natural logarithms of urbanization-free degree-days, land area, and the county sprawl index (the main interest of this study).

Results

Housing stock and energy use

From table 2, all end-use energy demands decrease with increasing energy price, increase with increasing annual household income, and vary by race/ethnicity. After we control for these covariates, the amounts of delivered energy use for space heating, cooling, and all other uses are strongly related to the physical characteristics of housing units. Old houses are less energy efficient than new ones. Detached houses require more energy than attached ones. Compared with households living in multifamily units, otherwise comparable households living in single-family detached units consume 54 percent more energy for space heating and 26 percent more energy for space cooling. Not surprisingly, energy for heating, cooling, and all other uses increases with house size. Compared with a household living in a 1,000-square-foot house, an otherwise comparable household living in a 2,000-square-foot house consumes 16 percent more energy for space heating and 13 percent more energy for space cooling.

Urban form and housing stock

Housing mix varies across metropolitan counties. Among the 448 counties in this sample, the highest share of multifamily housing is 99 percent in New York County, which has a county sprawl index of 352 (reflecting the fact that compact places have higher values), while the lowest is 0.6 percent in New Kent County, VA, which has an index of 73. Some of the difference in housing mix is related to sociodemographics, and some is related to urban form.

From table 3, the likelihood of choosing a single-family attached or multifamily home declines as the number of people in the household and the annual household income increase; to wit, larger and higher-income households are more likely to opt for a single-family detached home. The likelihood of choosing a single-family attached or multifamily home is greater for black, Hispanic, and Asian households than for white households and increases with residential construction costs. After we control for these covariates, people's choice of house type is strongly related to urban form. The odds that a household will live in multifamily housing are seven times greater for compact counties, one standard deviation above the mean index, than for sprawling counties, one standard deviation below the mean index (that is, a 50-point spread).

Median house size also varies across metropolitan counties. Among the 59 counties in this sample, the smallest median house size is about 1,000 square feet in San Francisco County, with an index of 209, and the largest is approximately 2,300 square feet in Waukesha County, WI, with an index of 90. Again, some of the difference in house size is related to sociodemographics, and some is related to urban form.

From table 4, house size increases with the number of people in the household and with annual income. It is larger for white households than for black, Hispanic, or Asian households. No statistically significant connection to residential construction costs or metropolitan area size was found. After we control for these covariates, the choice of house size is significantly related to urban form. Houses are 23 percent larger in sprawling counties, one standard deviation below the mean index, than in compact counties, one standard deviation above the mean index.

Temperatures and space-conditioning energy use

From table 2, after we control for all other influences, total delivered energy use for space heating and cooling per household per year increases with the number of HDDs or CDDs, respectively. At a 95 percent confidence level, for example, 10 extra HDDs are associated with a 0.2 percent increase in energy use for heating, or about 88,000 BTUs of primary energy per year, while 10 extra CDDs are associated with a 0.5 to 0.6 percent increase in energy use for cooling, around 42,000 BTUs per year.

Urban form and temperatures

Due to the UHI effect, temperatures are higher than they would be otherwise, and the effect is greater in compact counties than in sprawling ones. From table 5, with each 1 percent increase in the county sprawl index (which means an increase in compactness), the number of observed HDDs decreases by 0.21 percent, while the number of observed CDDs increases by 0.48 percent.

Synthesis

After controlling for household characteristics, we now know that residential energy use varies with house type and house size and that these vary the degree of urban sprawl. These relationships, taken together, allow us to indirectly estimate the effects of urban sprawl on residential energy use through the mediators of house type and size. The average household would be expected to consume 17.9 million fewer BTUs of primary energy annually, about 20 percent less, living in a compact county, one standard deviation

Table 5. Relationship between Observed HDDs and CDDs, Urban Sprawl, and Other Controls in the United States (with Coefficients and Significance Levels)

	Observed HDDs		Observed CDDs	
	Coefficient	*p*-Value	Coefficient	*p*-Value
Ln (sprawl index)	–0.215	–0.036	0.480	< 0.000
Ln (urbanization-free HDD)	1.417	< 0.000	NA	NA
Ln (urbanization-free CDD)	NA	NA	0.659	< 0.000
Ln (area)	–0.079	0.001	0.188	0.001
Topographic feature				
Coast	–0.120	0.044	–0.104	0.060
Valley	–0.137	< 0.000	–0.204	< 0.000
R^2	0.9139		0.8140	
Number of counties	543		543	

Sources: ESRI (2005), Ewing et al. (2003), and Kalnay and Cai (2003).
Notes: The dependent variable is the number of observed HDDs and CDDs.
Ln = natural log; NA = not applicable.

above the mean index, than in a sprawling county, one standard deviation below the mean index.

We also know that the UHI effect is strongest in compact areas, that it leads to an increase in CDDs and a reduction in HDDs, and that these in turn affect energy use for space heating and cooling. These relationships, taken together, allow us to estimate the indirect effects of urban sprawl on residential energy use through the mediating effect of UHIs. Nationwide, because of UHIs, an average household in a compact county would be expected to consume 1.4 million fewer BTUs of primary energy annually than an average household in a sprawling county.

Throughout most of the nation, the two effects, housing and UHI, are in the same direction. The exceptions are in the Sunbelt, where more compact development provides an energy savings because of the greater prevalence of attached housing and smaller units, but creates an energy penalty because of higher urban temperatures and greater demands for space cooling. Everywhere, the housing effect is much stronger than the UHI effect, so urban sprawl can be said to inflate residential energy consumption and associated greenhouse gas emissions regardless of location.

Policy implications

Energy conservation, and the associated reduction in greenhouse gases, can be thought of as just one more reason to encourage compact development and discourage sprawl. Compact development provides a double benefit, typically reducing transportation energy use and emissions by 20 to 40 percent relative to sprawl (Ewing et al. 2008) and having a comparable percentage impact on residential energy use and emissions. As worldwide peak production of conventional oil approaches, transitioning to compact development in this country can cushion the blow of a rapid rise in energy prices. And as the world strives to stabilize climate, compact development can help the United States meet targets for reducing greenhouse gas emissions.

Strategies for encouraging compact development and discouraging sprawl follow directly from our operational definition of sprawl. Residential densities can be boosted by raising zoning density caps, establishing density floors, reducing minimum lot sizes, offering density bonuses, charging impact fees, creating urban growth boundaries or urban service limits, transferring development rights, or promoting downtown redevelopment (Dawkins and Nelson 2003; Landis 2006; Pendall 1999, 2000; Shen and Zhang 2007). Oregon-style growth management has been found to be particularly effective in raising densities (Carruthers 2002). Street accessibility can be increased by establishing street connectivity requirements, maximum block sizes, bans or length limits on cul-de-sacs, external street connection requirements, or stub-out requirements (Butler, Handy, and Paterson 2003).

Of course, these same ends can be achieved by targeting the housing stock directly. The biggest energy savings come from the transition from detached to attached single-family housing or detached to multifamily housing. To some degree, this transition is occurring anyway because of demographic and other societal changes (Ewing et al. 2008; Myers and Gearin 2001). But it could be helped along by changes in local zoning codes and maps, such as rezoning for more multifamily and attached housing, creating new zoning districts that allow intense mixed-use development, raising maximum building heights, and establishing minimum density requirements in centers of activity.

To discourage McMansions and other housing deemed oversized, quite a few municipalities have adopted or are considering limits on gross floor area for single-family houses (Nasar, Evans-Cowley, and Mantero 2007). These limits tend to be high (more than 5,000 square feet in some places) and therefore affect only a small percentage of all single-family home construction. More restrictive—and significant for energy conservation—may be regulations limiting floor area ratios, lot coverage, or daylight planes of single-family homes or regulations limiting tear-downs or requiring design review (Szold 2005). The recent adoption of a maximum floor area ratio of 40 percent (or 2,300 gross square feet, whichever is greater) in Austin (TX) was a direct response to the mansionization of one neighborhood. "Regulations must fit a valid public purpose. Controlling oversized houses, which can impact sound, traffic, light, and aesthetics, fits well within that public purpose" (Nasar, Evans-Cowley, and Mantero 2007, 343).

Limitations

This study is exploratory and subject to important limitations. First, because no single database provides all the necessary data, this study used different sources to examine the impact of urban sprawl on residential energy use through housing stock and UHI effects. The compounding of measurement errors from equation to equation requires caution regarding the estimates. The availability of more consistent and comprehensive data is the key to better research in this area.

Second, because of data limitations, we could not account for some factors that might confound the relationship between sprawl and residential energy use. For example, we could not capture differences in building code and demand-side management programs in the housing stock and energy use models, and we could not control for complex local influences such as park space and street tree canopy in the UHI intensity and sprawl model. Future research should attempt to account for these factors.

Third, urban sprawl affects residential energy use through electricity T&D losses, in addition to the causal pathways explored in this article. Distributed electricity generation, that is, power generation sited at the "load," may eventually reduce the energy penalty associated with sprawling land use patterns. Until then, sprawl will produce electricity T&D losses of unknown but potentially significant magnitude.

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