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Analysis

A multivariate analysis of the energy intensity of sprawl versus compact living in the U.S. for 2003

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ABSTRACT

We explore the energy intensity of sprawl versus compact living by analyzing the total energy requirements of U.S. households for the year 2003. The methods used are based on previous studies on energy cost of living. Total energy requirement is calculated as a function of individual energy intensities of goods and services derived from economic input–output analysis and expenditures for those goods and services. We use multivariate regression analysis to estimate patterns in household energy intensities. We define sprawl in terms of location in rural areas or in areas with low population size. We find that even though sprawl-related factors account for about 83% of the average household energy consumption, sprawl is only 17–19% more energy intensive than compact living based on how people actually lived. We observe that some of the advantages of reduced direct energy use by people living in high density urban centers are offset by their consumption of other non-energy products. A more detailed analysis reveals that lifestyle choices (household type, number of vehicles, and family size) that could be independent of location play a significant role in determining household energy intensity. We develop two models that offer opportunities for further analysis.

1. Introduction

1.1. Context

There are many compelling reasons for supporting compact development and a high level of household consumption in general, but here we are concerned specifically with the energy required to support that lifestyle. We explore the question of how much difference compact living makes when compared to sprawl in terms of total energy use by households. Newman and Kenworthy (1999) claim that residents in compact areas drive between one-third and one-fourth as much as do residents of areas characterized by sprawl. Another study by the Natural Resources Defense Council shows that as density doubles, automobile use may drop as much as 40% (Benfield et al., 1999). These findings, looking at only the transportation impact of sprawl, are often extrapolated to imply that the difference is large, perhaps a factor of two or more, especially if other aspects' consumption were to be considered. However, one should consider two complicating issues:

1. Money saved through reduced direct energy use — by walking instead of driving, for example — is often spent on other, non-energy products that themselves require energy.
2. The comparison of households requires accounting for different total expenditure amounts (the level of affluence), usually through a comparison of the households' energy intensity, i.e., the average energy consumed per dollar spent by each and the total energy used by households over a given time period.

These two issues have been addressed in “energy cost of living” studies starting around 1973 and continuing today (Bullard and Herendeen, 1975; Herendeen and Tanaka, 1976; Herendeen, 1978; Bullard et al., 1978; Herendeen et al., 1981; Vringer and Blok, 1995; Lenzen, 1998; Pachauri, 2004; Carlsson-Kanyama et al., 2005; Moll et al., 2005; Holden and Norland, 2005; Bin and Dowlatabadi, 2005; Lenzen et al., 2006; Norman et al., 2006). All these studies have used a combination of energy intensities of consumer expenditures derived from economic input–output accounts along with surveys of consumer expenditure patterns. Because of data limitations, none of these studies have an unambiguous method for differentiating urban versus rural settings or compact living versus sprawl. Some do, however, make an effort in that direction. Results from several studies show that rural

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Table 1
Description of terms and symbols used in this paper.

Symbol/term	Definition	Units
$\Delta\varepsilon_{avg}$	Change in average household energy intensity	Btu/$
ε_{ip}	Energy intensities in producers' price from EIO-LCA (EIO-LCA, 2006)	Btu/$
f_{ip}	Fraction of the purchasers' price paid for product i	
f_{im}	Fraction of price paid for margin m of product i	
ε_i	Energy intensity of product i including the margins in purchasers' price	Btu/$
Y_i	Expenditure on item i in thousands of dollars	$/yr
Y	Total household expenditure in thousands of dollars	$/yr
α	Exponent in the regression model (also, the expenditure elasticity of energy)	
D_i	Dummy variable for demographic predictor i	
$f_i(D_i)$	Multiplicative effect of the demographic predictor i	
η_{D_i}	Partial regression coefficients dummy variable i	
s^2	Error variance ((residual mean square, RMS) in logarithmic form	
μ	Mean of error term in log-transformed regression model	
ΔX	Change (or error) in X where, $X = E, \varepsilon_i, Y_i, K, \alpha$	
BEA	U.S. Bureau of Economic Analysis	
BLS	U.S. Bureau of Labor Statistics	
Btu	1 Btu = 1055 J	Btu
E	Energy consumption per year	Btu/yr
EIO-LCA	Economic Input Output-Life Cycle Assessment	
Energy cost of energy	Total primary energy/energy of given type delivered to purchaser	
Energy intensity, ε	Energy per dollar spent	Btu/$
GDP	Gross domestic product	$/yr
K	Intercept of the regression model	
MBtu	Million Btu	MBtu
PCE	Personal consumption expenditure	$/yr
Quad	10^{15} Btu	

households typically have about 10% higher energy intensities than urban households (Herendeen, 1978; Herendeen et al., 1981; Lenzen, 1998). This paper updates the U.S. results to the year 2003.

1.2. Sprawl and Energy

In the conventional literature, suburban and rural households, often characterized as sprawl, are claimed to be more energy intensive than households in dense, compact central city locations, which are often described as "compact living" (Gillham, 2002; Burchell et al., 2005; Holden and Norland, 2005). This difference is implicitly related to lifestyle and consumption patterns of households located in different spatial configurations. Residences in central cities are assumed to be smaller and more compact, thus requiring less energy. They are also assumed to depend less on automobiles because of better access to mass transit, more walkable neighborhoods, proximity to shopping and schools, and the higher cost of maintaining personal vehicles. Thus, a move toward compact living instead of sprawl would be expected to significantly reduce energy consumption (Gillham, 2002; Newman and Kenworthy, 1999). However, household energy consumption is not restricted to residential and vehicular fuel (i.e., direct energy); all human activities have energy implications. Therefore, a system boundary drawn around direct use of energy only would yield an incomplete assessment of household energy use. A given household can have different energy requirements based on different consumption patterns that support its lifestyle. If we draw the system boundary around consumption patterns in general, then we must include all the indirect energy associated with all other household consumption. This approach provides a better understanding of the energy intensity and total energy consumption of households in the context of various spatial and demographic predictors.

The definition of sprawl itself has been a controversial topic for decades. We define sprawl as rural areas or areas with low population size in our analysis. Contemporary literature on sprawl also attributes one or more of the following characteristics to this type of development: outward expansion from central business district into undeveloped areas, discontinuous or "leapfrog" development, rigid separation of housing and commercial development, high automobile dependence, poor accessibility, lack of well-defined activity centers, and scattered development without systematic large-scale or regional land-use planning (Galster et al., 2001; Ewing et al., 2002; Bruegman, 2005; Burchell et al., 2005). Perhaps the most comprehensive studies that explore the resource impact of sprawl have been produced by the Transit Cooperative Research Program (TCRP) in two reports on the costs of sprawl (Burchell et al., 1998, 2000). These studies were motivated by a 1974 analysis by the Real Estate Research Corporation (RERC) entitled *The Costs of Sprawl* (RERC, 1974) and consider the impacts of sprawl on infrastructure, transportation, energy, environment, and quality of life.

In this paper we estimate the energy intensity and total energy consumption of households in sprawl versus compact living. Although we analyze the entire spectrum of household expenditures, we pay particular attention to "sprawl-related" expenditures. These include all housing-related expenditures, including residential fuel and all vehicle-related expenditures, including gasoline. We statistically analyze the effects of spatial variables such as location (urban versus rural) and degree of urbanity (population size of the area of residence) on energy consumption. We compare these effects with other demographic predictors such as family size, number of vehicles, and building type. A list of terms and symbols used in this paper is given in Table 1.

2. Method

2.1. General Framework

We estimate the total energy requirements for households by multiplying expenditures in dollars by appropriate energy intensities in British thermal units (Btu) per dollar (1 Btu = 1055 J). We use expenditure as the primary independent variable instead of income. By using expenditure, we avoid neglecting transfer payments (public assistance, social security benefits, etc.).

2.2. Energy Intensities

Bullard and Herendeen (1975) used input–output analysis to determine the energy intensities of various goods and services, as applied to 357 sectors in the U.S. economy for 1967. This analysis was used to determine potential energy savings resulting from changing consumption patterns. This work was later updated using 1977 data from the Bureau of Economic Analysis (BEA) (Hannon et al., 1985).

More recently, researchers at Carnegie Mellon University created the EIO-LCA database (Hendrickson et al., 1998; EIO-LCA, 2006) using more recent input–output data from the U.S. Department of Commerce. The software traces the various economic transactions, resource requirements, and environmental emissions for a particular product or service. Energy intensities for 491 sectors are included as one of EIO-LCA's outputs. These intensities are given in producer prices. However, consumers pay purchaser prices (the sum of producer price and the trade and transportation margins). We convert intensities to producer prices as follows. Transportation and trade margins for each product category are from Bureau of Economic Analysis data (BEA, 2004); from them we calculate the fraction of the purchaser price that pays for product i (f_{ip}) and for each of the margins (f_{im}) so that $f_{ip} + \sum_{m=1}^{q} f_{im} = 1$, where the sum is over the transportation and trade margins (Bullard and Herendeen, 1975). Intensities are then converted to purchaser prices (ε_i):

$$\varepsilon_i = \varepsilon_{ip} \times f_{ip} + \sum_{m=1}^{q} \left(\varepsilon_{mp} \times f_{im}\right).$$

Since we have only one intensity for each margin, we must assume, for example, that a dollar worth of rail transport requires the same energy independent of the product carried. In addition, we modified the energy intensities from EIO-LCA for motor fuel and residential oil, natural gas, and electricity. This was necessary because EIO-LCA uses a published dollar-based inverse matrix from BEA that does not adequately reflect the physical flows between energy sectors (e.g., crude oil and gas extraction, and petroleum refineries). This problem can be removed by creating a "mixed" transactions matrix in which flows from energy sectors are expressed in physical units and flows from non-energy sectors are expressed in monetary units. One then performs the standard input–output analysis on this mixed matrix (Bullard and Herendeen, 1975). EIO-LCA did not use the mixed approach. We therefore combined the indirect energy obtained using energy intensities from EIO-LCA with the direct energy obtained using pricing data from the U.S. Energy Information Administration (EIA) and BEA (Herendeen, 1973). For example, \$1 spent for refined petroleum would require energy of (\$1 × EIO-LCA's intensity for refined petroleum + energy content of refined petroleum × \$1 / (price of refined petroleum)). Our results for "energy cost of energy" (total primary energy / energy of given type delivered to purchaser) are consistent with previous results and expectations: motor gasoline, 1.24; natural gas, 1.06; heating oil, 1.22; and electricity, 3.87.

2.3. Consumer Expenditures

The BLS Division of Consumer Expenditure Surveys conducts a nationwide survey of consumer expenditures every year and publishes results aggregated at the national level. The detailed household-level data are available from BLS in the form of Public Use Microdata containing information on expenditure, income, and other demographic variables (BLS, 2004). The data set includes two surveys: an Interview Survey and a Diary Survey. The Diary Survey has not been used in this study as it contains only 2 weeks of data for any given household. The Interview Survey, however, contains five fiscal quarters of data. The surveys are based on interviews conducted between January 2003 and March 2004. These data serve as the basis for the analysis performed in this study.

Since BLS uses a rotating panel of households, we generated a sub-sample of the BLS data that contained only those households that participated in four consecutive quarters. This approach resulted in a reduced sample size. The BLS Interview Survey includes 18,573 households generating 40,374 independent samples using a balanced repeated half-sample replication method for weighting and aggregation, but we found only 2982 households that participated in four consecutive quarters. The annual data for these households actually represent expenditures made over 12 consecutive months occurring anytime between October 2002 and February 2004. Also, BLS uses a stratified random sample in selecting the households that participate in the Interview Survey. By reducing the sample size based on the arbitrary criterion of annual data availability we may have inadvertently lost some of the stratification and randomness in our sub-sample.

Table 2
Description of composite categories created to analyze the composition of household energy requirements in terms of direct energy versus indirect energy and sprawl-related energy versus non-sprawl energy.

Aggregated category	Description
Direct Energy	All residential fuel (including electricity) and auto fuel — including the energy cost of energy
Indirect Energy	All expenditures except those in Direct Energy
Sprawl-related	Direct Energy and all non-direct energy expenditures on housing and automobile
Non-sprawl	All expenditures except those in Sprawl

We had to address two other issues in determining our final sample. First, we discarded 128 households that had null values for residential fuel and electricity from the data set in order to avoid cases where rental expenditures may include the cost of utilities. Second, we dropped 60 households with incomplete data. Our final sample includes 2794 households. The income distribution of our sample matches closely with the U.S. national distribution for 2003 published by BLS.

2.4. Matching and Aggregation

The consumer expenditure data from BLS compile household expenditure and income information at a highly disaggregated level (more than 600 categories). We created 52 aggregated expenditure categories that match the categories in published BLS data and the aggregated energy intensities from EIO-LCA. While the expenditure data are from 2003, the energy intensities are from 1997. We updated the intensities to a value in 2003 dollars by using product-specific consumer prices (PI_i). We also accounted for changes in technology by using the ratio of the total energy consumption by the U.S. economy (E) to gross domestic product (GDP), as illustrated in the equation below. The final intensities used in this paper are expressed in terms of 2003 dollars and 2003 technology. All dollar values used here are in constant dollars.

$$\varepsilon_{i(2003,2003)} = \varepsilon_{i(1997,1997)} \times E_{2003} / GDP_{2003} \times GDP_{1997} / E_{1997} \times PI_{(1997)} / PI_{(2003)}$$

In addition to the demographic variables in the BLS data set we created four composite variables for the purpose of our analysis, as shown in Table 2. Consumers spend money on direct energy (electricity, natural gas, gasoline, etc.) and indirect energy (all other products). We created two composite categories to explore how direct and indirect energy requirements vary with expenditure. We also created two other composite categories to analyze the difference in total household energy requirements between sprawl and non-sprawl settings.

Energy intensities for the aggregated expenditure categories are calculated using the weighted average of the intensities of the disaggregated expenditure categories based on national average consumer expenditures in the respective categories for 2003. The energy intensities for the composite categories have also been calculated in the same way.

The aggregated, composite, and disaggregated energy intensities are presented in Table 3. We calculated the energy requirements using energy intensities at the most disaggregated level possible.

The energy intensities from EIO-LCA (2006) do not include the energy to support labor involved in producing the goods and services. This is the standard practice in the methods used in this paper. See Costanza and Herendeen (1984) for a discussion on this. We do not

Table 3
Energy intensities of various expenditure categories are shown for 2003 dollars and 2003 technology. Our calculations for the aggregated categories are based on the most disaggregated level possible (right-indented). Labels: D = Direct, I = Indirect, S = Sprawl-related and NS = Non-sprawl.

Categories			Energy intensity (Btu/$)		Label
Highly aggregated categories					
Average Energy Intensity (all categories)			12,000		
Average Intensity of Direct Energy			118,100		D
Average Intensity of Indirect Energy			4600		I
Average Intensity of Sprawl-related Energy			18,200		S
Average Intensity of Non-sprawl			4200		NS
BLS expenditure categories at various levels of aggregation					
Residential fuel/electric			139,300		D, S
	Natural gas		114,700		D, S
	Electricity		151,800		D, S
	Fuel oil/other fuels		111,300		D, S
Vehicle fuel	Gasoline/motor oil		94,300		D, S
Housing			4600		I, S
	Owned dwellings		3500		I, S
		Mortgage interest/charges		2000	I, S
		Property taxes		0	I, S
		Maint./repairs/insurance/other		12,800	I, S
	Rented dwellings			3700	I, S
	Other lodging			5000	I, S
	Public services		4200		I, S
		Telephone services		2600	I, S
		Water/other public services		8900	I, S
	Household operations		2500		I, S
		Personal services		2700	I, S
		Other household expenses		4200	I, S
	Housekeeping supplies		5200		I, S
		Laundry and cleaning supplies		6100	I, S
		Other household products		4400	I, S
		Postage and stationery		5600	I, S
	Household furnishings and equipment		5000		I, S
		Household textiles		7400	I, S
		Furniture		6100	I, S
		Floor coverings		7400	I, S
		Major appliances		7000	I, S
		Small appliances/misc. housewares		5500	I, S
		Misc. household equip.		5800	I, S
	Housing structure			7800	I, S
Vehicle purchase/maintenance			5500		I, S
	Vehicle purchases (net outlay)		7300		I, S
		Cars/trucks (new)		7000	I, S
		Cars/trucks used)		7600	I, S
		Other vehicles		10,300	I, S
	Other vehicle expenses		2500		I, S
		Vehicle finance charges		1900	I, S
		Maint. and repairs		4300	I, S
		Vehicle insurance		1000	I, S
		Rental/leases/other		2700	I, S
Public transport				21,300	I, NS
Food			6100		I, NS
	Food at home			6700	I, NS
	Food prepared on out-of-town trips			6500	I, NS
	Food away from home			5200	I, NS
Alcohol/tobacco			3700		I, NS
	Alcoholic beverages			4900	I, NS
	Tobacco products and smoking supplies			1800	I, NS
Apparel and services			6500		I, NS
	Apparel (men, boys, girls, children)			6600	I, NS
	Footwear			6200	I, NS
	Other apparel products and services			6500	I, NS
Health care/personal care			2400		I, NS
	Health care		2100		I, NS
		Health insurance		1000	I, NS
		Medical services		2700	I, NS
		Drugs		3600	I, NS
		Medical supplies		3500	I, NS
	Personal care products and services			3900	I, NS
Entertainment			3800		I, NS
	Fees and admissions			2800	I, NS
	Television, radios, sound equipment			4600	I, NS
	Pets, toys, and playground equipment			6500	I, NS
	Other entertainment supplies, equipment, services			5300	I, NS

Table 3 (*continued*)

Categories		Energy intensity (Btu/$)	Label
Reading/education			I, NS
	Reading	3500	I, NS
	Education	2900	I, NS
Cash contributions		3800	I, NS
Personal insurance and pensions		1600	I, NS
Miscellaneous		4200	I, NS

consider taxes in our calculation because taxes are a population's collective input to government expenditures, and therefore it would not be justifiable to assign to individual consumers the energy burden resulting from the public expenditure of tax revenues.

2.5. Limitations

One limitation of this method is the assumption of constant proportions: energy use is assumed to increase linearly with

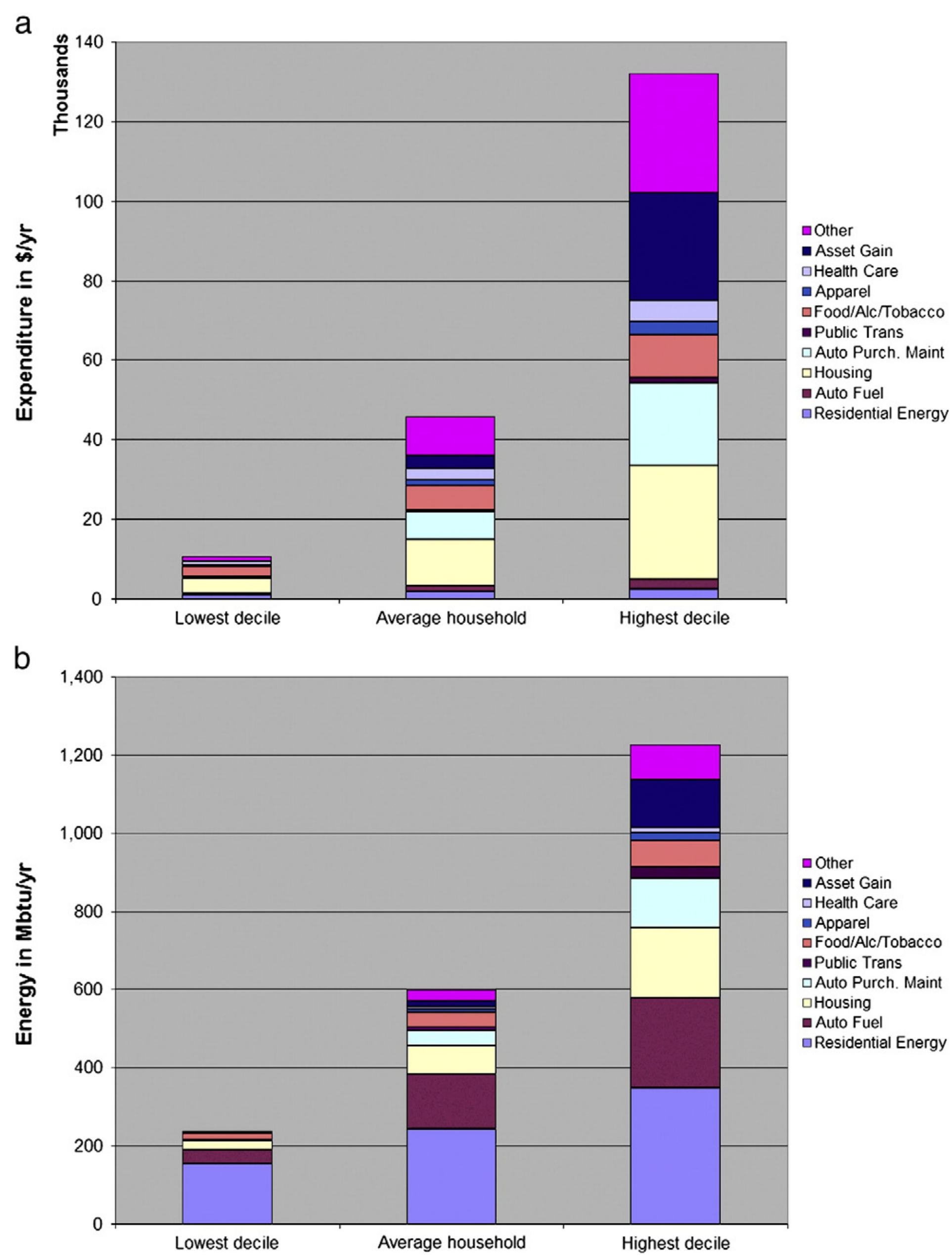

Fig. 1. (a) Monetary expenditures of the lowest expenditure decile with a mean expenditure of $11,509/yr, average household with a mean expenditure of $49,261/yr and highest expenditure decile with a mean expenditure of $140,151/yr. (b) Corresponding energy requirements of the lowest expenditure decile with a mean energy requirement of 238 Mbtu/yr, average household with a mean energy requirement of 599 MBtu/yr, and highest expenditure decile with a mean energy requirement of 1226 MBtu/yr.

expenditure for a specific good. For example, a shirt worth $100 is assumed to use the same energy as two shirts worth $50 each. Also, the method does not distinguish between different product types within a given category. For example, the amount of energy required to construct a large, $400,000 single-family home is assumed to be the same as a small, upscale $400,000 high-rise apartment unit.

We apply energy intensities at a higher level of aggregation where the subcategories may have different energy intensities. Even though we use appropriate weighting schemes to minimize the errors in our estimate, there will still be residual errors as each household spends differently on the subcategories that have been aggregated. For example, all pets, toys, and playground equipment have been combined into one category and assigned the same energy intensity even though individual household expenditures and the associated energy intensities under this category may vary widely.

We express energy intensities in Btus per dollar. The use of dollars as a unit of measure poses a problem because the price of goods and services varies with location. We could not correct this problem for each household in our sample because the detailed household location information was not available due to nondisclosure requirements. Certain volatile items such as real estate prices are of particular concern. Data from the National Association of Realtors show large variability in real estate prices. The highest price index among all metropolitan areas in the United States (San Francisco, California) is about six times larger than the lowest (Beaumont/Port Arthur, Texas). In the end, we adjusted only for overall price variations based on regional differences in consumer price indices.

In our analysis we assume that imports have the same energy intensities as their domestic counterparts (Lenzen, 2000; Peters and Hertwich, 2005a,b; Hendrickson et al., 2006). This is done for convenience, but over the years it has become less defensible as globalization has increased the relative scale of international trade, and several quantitative analyses have been published. Weber and Matthews (2008) found that about 30% of the CO_2 emissions supporting U.S. households occurred outside the country. From Peters and Hertwich (2008), we estimate that figure, i.e., CO_2 emissions from imports to total U.S. CO_2 emissions at 16%. From that source we also estimate 8% for exports, giving a net of 8% for imports. Hertwich and Peters (2009), again for CO_2, find U.S. import/domestic at 18% for the year 2001. From a web site based on the latter article (Carbon Footprint of Nations, 2009), we estimate the U.S. net import fraction at 13%. We conclude that the overall U.S. energy impact is of order 10% greater than domestic consumption. If that is equally true for all products, our comparison of sprawl/compact, rural/urban will be unaffected. If it varies over products, it could affect our results. For this article, we acknowledge its potential impact as an additional source of uncertainty.

Finally, some capital expenditures made by a household are spread over a long period of time, such as the market value of an owned home. We annualized this expenditure using straight-line depreciation based on the long-term (20 year) yields on U.S. treasury bonds, about 2.5% per year (U.S. Department of Treasury, 2006).

Table 4
Shares of expenditure and energy for direct energy and sprawl-related categories for the lowest expenditure decile, average household and highest expenditure decile for U.S. households, 2003.

	Expenditure (%)		Energy requirements (%)	
	Direct	Sprawl-related	Direct	Sprawl-related
Lowest decile	13	57	80	90
Average	6	52	64	82
Highest decile	4	45	47	72

Table 5
Results are shown for the univariate regression model for aggregated categories with total energy as the dependent variable and total expenditure as the independent variable. All parameters have been estimated for annual expenditures (Y) in multiples of U.S. $1000 and annual energy in Million Btus (MBtu). Here, SE = Standard Error.

E	K ± SE	α ± SE	R^2
Total	45.18 ± 1.3	0.68 ± 0.01	0.73
Direct	64.13 ± 2.8	0.48 ± 0.01	0.34
Indirect	3.61 ± 0.1	1.05 ± 0.01	0.94
Sprawl-related	51.44 ± 1.8	0.60 ± 0.01	0.55
Non-sprawl	2.20 ± 0.1	0.98 ± 0.01	0.80

3. Analysis and Results

3.1. General Framework

The general model used in this analysis for calculating total household energy requirements, E, is shown in Eq. (1):

$$E = \sum_{i=1}^{n} \varepsilon_i Y_i \tag{1}$$

where ε_i = energy intensity of item i and Y_i = expenditure on item i.

Energy intensities for all consumption categories are obtained in purchaser prices and multiplied with expenditure. Additionally, our estimate of total energy (E) includes the energy cost associated with the annualized value of an owned home (housing structure) and

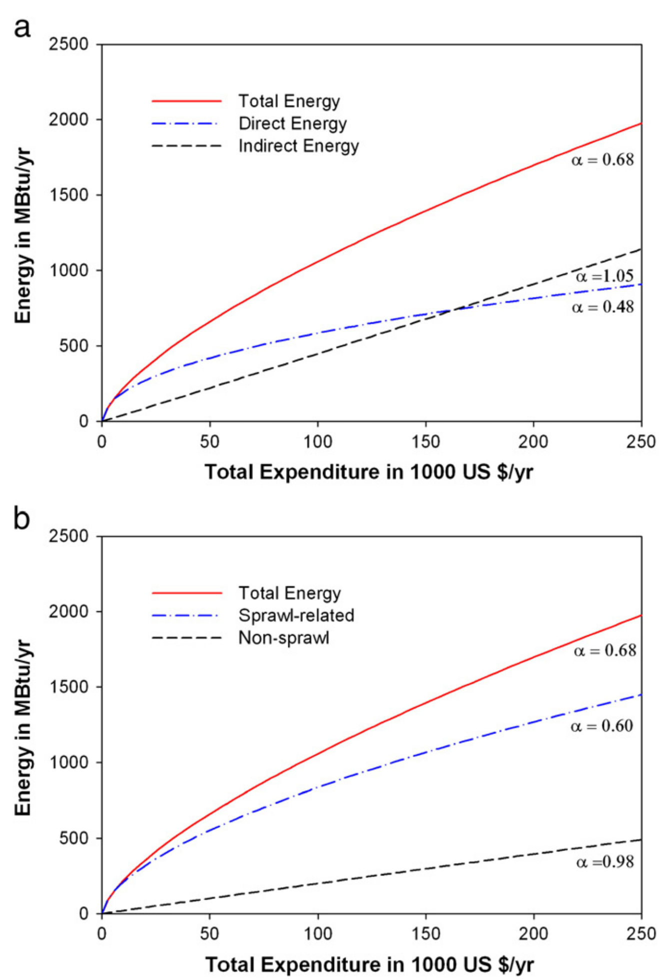

Fig. 2. Energy requirements of U.S. households for 2003 are shown for: (a) direct and indirect energy, and (b) sprawl and non-sprawl energy. Here, α is the expenditure elasticity of total energy.

positive changes in assets that include investments in stocks and bonds and capital improvements of owned property (asset gain). This is shown in Eq. (2):

$$E = \sum_{i=1}^{n} \varepsilon_i Y_i + \varepsilon_h Y_h + \varepsilon_a Y_a \quad (2)$$

where ε_h and ε_a = energy intensities of housing structure and asset gain, and Y_h and Y_a = annualized value of housing structure and positive changes in asset.

3.2. Graphical Analysis

Fig. 1 shows the aggregated consumption categories and corresponding energy requirements of the lowest and highest expenditure deciles and also those of the average household. Table 4 demonstrates how energy requirements vary for the composite categories.

We find that as expenditure increases, the contribution of direct energy to total energy requirements decreases, and for the highest decile more than 50% of total energy is attributable to indirect energy categories. It may be noted that the average direct energy intensity is almost 26 times higher than the average indirect energy intensity (see Table 3). This explains why direct energy dominates the total energy requirements of households. Because the sprawl-related category includes direct energy and all other housing and vehicle-related expenses, it accounts for an even larger share of the total energy requirements. While this tells us that the potential for changes in household energy demand are highly dependent on the sprawl-related categories, it is still important to look at total household energy consumption for a comprehensive comparison between households in different locations.

We compare our results with national estimates. We find that the total energy attributable to personal consumption is ca. 67 Quads/yr (10^{15} Btu) — thus accounting for about 68% of U.S. energy consumption in 2003. Based on the 2003 U.S. National Accounts, we find that personal consumption expenditures in the U.S. in 2003 accounted for about 70% of all expenditures.

3.3. Statistical Analysis

The graphical analysis conveniently summarizes the composition of total energy requirements for the households in our sample, but it does not provide a generalized framework for further analysis. To accomplish that goal we developed a statistical model that would allow us to analyze household energy requirements against the full range of expenditures and examine the effects of the composite variables (see Table 2) and demographic variables. We are particularly interested in the predictors associated with sprawl to learn how they impact total energy requirements.

We explore the nonlinear relationship between energy (E) and total expenditure (Y) using the univariate relationship presented in Eq. (3):

$$E = K \times Y^{\alpha}. \quad (3)$$

Table 6
Multivariate regression results are shown for the individual model with total energy as the dependent variable and total expenditure as the independent variable along with one demographic predictor at a time. All parameters are for annual expenditures (Y) in multiples of U.S. $1000 and annual energy in Million Btus (MBtu). Here, SE = Standard Error. The location-dependent effects are shaded.

Demographic predictor	Subcategory	K ± SE	α ± SE	$f_i(D_i)$ ± SE	Change in E %	R_2	Significance $p<0.05$
Region of residence							
Region	NE	41.84 ± 1.21	0.69 ± 0.01		0%	0.76	
	MW			1.04 ± 0.02	4%		Y
	S			1.14 ± 0.02	14%		Y
	W			0.86 ± 0.01	−14%		Y
Urban versus rural							
Urban/Rural	Urban	43.76 ± 1.24	0.68 ± 0.01		0%	0.73	
	Rural			1.17 ± 0.02	17%		Y
Degree of urbanity							
Popsize	>4 million	39.98 ± 1.23	0.69 ± 0.01		0%	0.74	
	1.2 to 4 million			1.05 ± 0.02	5%		Y
	0.33 to 1.19 million			1.14 ± 0.02	14%		Y
	125 to 329.9 K			1.06 ± 0.02	6%		Y
	Less than 125 K			1.19 ± 0.02	19%		Y
Number of vehicles							
Vehicles	0	47.55 ± 1.44	0.61 ± 0.01		0%	0.75	
	1			1.13 ± 0.02	13%		Y
	2			1.27 ± 0.03	27%		Y
	3			1.34 ± 0.03	34%		Y
	4			1.40 ± 0.04	40%		Y
	5 or more			1.43 ± 0.04	43%		Y
Household size							
Family size	1	47.45 ± 1.29	0.62 ± 0.01		0%	0.76	
	2			1.21 ± 0.02	21%		Y
	3 to 4			1.28 ± 0.02	28%		Y
	5 or more			1.35 ± 0.03	35%		Y
Building type							
Building	Apartment	39.25 ± 1.08	0.63 ± 0.01		0%	0.77	
	Town/rowhouse, Duplex–4 plex			1.23 ± 0.03	23%		Y
	Single family			1.44 ± 0.02	44%		Y
	Mobile home			1.49 ± 0.04	49%		Y
	Other (dorm, etc.)			1.10 ± 0.13	10%		N

Similar functional forms have been used by Herendeen et al. (1981), Pachauri (2004), and Lenzen et al. (2006). In addition to Eq. (1), we tested two other functional forms: (a) $E=(A+BY)(1-Ce^{-\beta Y})$ and (b) $E=k_1Y^{\alpha}+k_2Y$. The former expression was used by Herendeen et al. (1981) and the latter was designed retrospectively to capture the nonlinear trends in direct energy and the linear trends in indirect energy that we observed in this work. However, we could not find a reasonable regression fit with our data for these two models.

In order to incorporate the demographic predictors, we expand Eq. (3) to a multivariate form with n dummy variables, as presented in Eq. (4):

$$E = K \times Y^{\alpha} \times f_1(D_1) \times f_2(D_2) \times \ldots\ldots \times f_n(D_n) \tag{4}$$

where $f_i(D_i)$ = multiplicative effect of dummy variable i.

We log transformed the functional forms in Eqs. (3) and (4) for ordinary least squares regression (Eqs. (5) and (6)). This is useful as the statistical theory of linear relationships is highly developed and provides more dependable estimates. Also, the log-transformed variables better satisfy the assumptions of parametric statistics such as homoscedasticity and normality (Smith, 1993).

$$\ln E = \ln K + \alpha \ln Y \tag{5}$$

$$\ln E = \ln K + \alpha \ln Y + D_1 + D_2 + \ldots\ldots + D_n \tag{6}$$

Multiple regression of Eq. (6) yields estimates of K, α, and partial regression coefficients (η_{D_i}) for the dummy variables (D_i). Estimates for the nonlinear form are obtained by taking the exponent of the intercept and the partial regression coefficients. Thus, $K=\exp(\ln K)$ and $f_i(D_i)=\exp(\eta_{D_i})$. It should be noted that this is subject to retransformation bias. Eqs. (5) and (6) omit the error term because the mean of the error is zero in the logarithmic form ($\mu=0$). However, as soon as we retransform, the mean of the error term becomes ($\mu+0.5s^2$) where s^2 is the error variance (residual mean square) of the equation in logarithmic form. This results in an underestimate of E in Eq. (4) (about 5%), and we correct this by multiplying K by exp ($0.5s^2$) (Smith, 1993; Stow et al., 2006).

3.3.1. Univariate Regression Analysis

We perform univariate regression analysis using Eq. (5) to analyze the relationship between energy and expenditures and derive the parameters applicable to Eq. (3). We look at total energy, direct and indirect energy, and sprawl and non-sprawl energy. The results are shown in Table 5. The R^2 values are reasonable except in the case of direct energy, which is most likely because of the large variability of direct energy use by households (e.g., households with no cars versus households with several cars).

In Fig. 2 we observe that direct energy intensity diminishes with increasing expenditure while the relationship between indirect energy and expenditure is almost perfectly linear. Indirect energy use by households equals direct energy use at an expenditure of about $156,000, and beyond that expenditure level, households use more indirect energy than direct energy.

3.3.2. Multivariate Regression Analysis: Individual Model

Here we use Eq. (6) to perform multivariate regression analysis in which each sprawl-related demographic variable is treated individually to derive the parameters for Eq. (4). Results are presented in Table 6 and Fig. 3 that show that location-dependent variables — urban versus rural settings and populations of more than 4 million versus populations of less than 125,000 — are associated with a change in energy intensity of 17% and 19% respectively. At the same time, we see large effects in several location-independent variables, specifically, number of vehicles (up to 43%), family size (up to 35%), and building type (up to 49%).

The following example, using Table 6, illustrates the application of the individual model for two different households with the same annual expenditure of $50,000: one household with no cars and the other with three cars. We estimate total energy requirement (E) and energy intensity (ε) for each household.

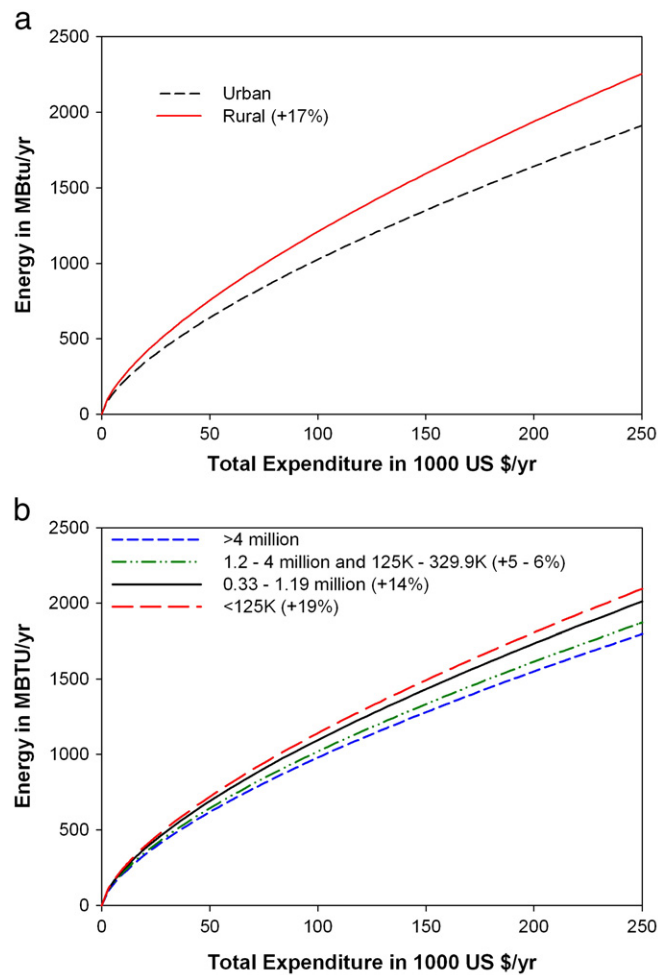

Fig. 3. Effect of the following demographic predictors on the U.S. household energy requirement for 2003: (a) urban versus rural locations, (b) population size of the area of residence.

Household with no cars:

$$E = 47.55 \times 50^{0.61} = 517 \text{ MBtu/yr}$$
$$\text{Average } \varepsilon = (517 \times 10^6) / 50{,}000 = 10{,}340 \text{ Btu/\$}$$

Household with three cars:

$$E = 47.55 \times 50^{0.61} \times 1.34 = 693 \text{ MBtu/yr}$$
$$\text{Average } \varepsilon = (693 \times 10^6) / 50{,}000 = 13{,}860 \text{ Btu/\$}$$

3.3.3. Multivariate Regression Analysis: Combined Model

In this analysis we use Eq. (6) to include all the sprawl-related variables to develop two multivariate regression models and derive the corresponding coefficients for Eq. (4). In Model A we look at the effect of location-independent demographic predictors along with the location-dependent variable *urban/rural* (urban versus rural location of residence). We do the same in Model B, but instead of *urban/rural* we include the location-dependent variable *popsize* (population size within the area of residence). We process the two location-dependent variables in separate models due to high cross-correlation between them (0.66). Each household is different, and these models allow us to

Table 7
Multivariate regression results are shown for two variations of the combined model. Urban/rural and popsize have been treated separately in Model A and Model B respectively to avoid cross-correlation. All parameters are for annual expenditures (Y) in multiples of U.S. \$1000 and annual energy in Million Btus (MBtu). Here, SE = Standard Error. The location-dependent effects are shaded.

Model A				
K ± SE = 41.92 ± 1.26	α ± SE = 0.57 ± 0.01		R^2 = 0.80	
Demographic predictor	Subcategories	$f_i(D_i)$ ± SE	Change in E %	Sig. $p<0.05$
Urban/rural	Urban	1.00	0%	
	Rural	1.08 ± 0.02	8%	Y
Building	Apartment	1.00	0%	
	Town/rowhouse, Duplex–4 plex	1.18 ± 0.02	18%	Y
	Single family	1.33 ± 0.02	33%	Y
	Mobile home	1.36 ± 0.04	36%	Y
	Other (dorm, etc.)	1.08 ± 0.12	8%	N
No. of vehicles	0	1.00	0%	
	1	1.08 ± 0.02	8%	Y
	2	1.12 ± 0.02	12%	Y
	3	1.15 ± 0.03	15%	Y
	4	1.18 ± 0.03	18%	Y
	5	1.20 ± 0.03	20%	Y
Family size	1	1.00	0%	
	2	1.12 ± 0.02	12%	Y
	3 to 4	1.20 ± 0.02	20%	Y
	5 or more	1.25 ± 0.02	25%	Y

Model B				
K ± SE = 41.38 ± 1.32	α ± SE = 0.57 ± 0.01		R^2 = 0.80	
Demographic predictor	Subcategories	$f_i(D_i)$ ± SE	Change in E %	Sig. $p<0.05$
Popsize	>4 million	1.00	0%	
	1.2 to 4 million	1.00 ± 0.02	0%	N
	0.33 to 1.19 million	1.05 ± 0.02	5%	Y
	125 to 329.9 K	0.96 ± 0.02	−4%	Y
	Less than 125 K	1.07 ± 0.01	7%	Y
Building	Apartment	1.00	0%	
	Town/rowhouse, Duplex–4 plex	1.17 ± 0.02	17%	Y
	Single Family	1.33 ± 0.02	33%	Y
	Mobile home	1.36 ± 0.04	36%	Y
	Other (dorm, etc.)	1.08 ± 0.12	8%	N
No. of vehicles	0	1.00	0%	
	1	1.08 ± 0.02	8%	Y
	2	1.12 ± 0.02	12%	Y
	3	1.15 ± 0.03	15%	Y
	4	1.18 ± 0.03	18%	Y
	5	1.20 ± 0.03	20%	Y
Family size	1	1.00	0%	
	2	1.12 ± 0.02	12%	Y
	3 to 4	1.20 ± 0.02	20%	Y
	5 or more	1.25 ± 0.02	25%	Y

test the effects of different configurations of the sprawl variables under various scenarios. The results are presented in Table 7.

We illustrate the application of the combined model, using Table 7, in the following example for two households with the same annual expenditure of U.S. \$50,000 and family size of three persons: one household with no cars and living in an apartment in an urban area; the other with three cars and living in an area with a population size of less than 125,000. We use Model A for the former and Model B for the latter to estimate total energy requirements (E) and energy intensities (ε).

Urban household, apartment living, no cars, three persons:

$$\begin{aligned} E &= K \times Y^{\alpha} \times f_iD_i(Urban) \times f_iD_i(Apartment) \times f_iD_i(Vehicles = 0) \\ &\quad \times f_iD_i(Familysize = 3) = 41.92 \times 50^{0.57} \times 1 \times 1 \times 1 \\ &\quad \times 1.20 = 468 \text{ MBtu / year} \end{aligned}$$

$$\text{Average } \varepsilon = (468 \times 10^6) / 50,000 = 9,360 \text{ Btu / \$}$$

Low-density household, single-family home, three cars, three persons:

$$\begin{aligned} E &= K \times Y^{\alpha} \times f_iD_i(Popsize < 125\text{K}) \times f_iD_i(SingleFamily) \\ &\quad \times f_iD_i(Vehicles = 3) \times f_iD_i(Familysize = 3) \\ &= 41.38 \times 50^{0.57} \times 1.07 \times 1.33 \times 1.15 \times 1.20 \\ &= 756 \text{ MBtu / year} \end{aligned}$$

$$\text{Average } \varepsilon = (756 \times 10^6) / 50,000 = 15,120 \text{ Btu / \$}$$

Several points should be noted about the above framework. All demographic predictors have pair-wise correlation coefficients less than 0.2. However, we recognize that some correlation is expected to exist between the sprawl-related variables (see Section 4 for more on this). Also, one variable (*popsize* between 1.2 and 4 million) that was significant in the individual model turned out to be insignificant in the combined model, and contrary to the individual model, *popsize* between 125,000 and 330,000 turned out to be least energy intensive in the combined model. This result probably indicates that a smaller metropolis within this size range is in a better position to take advantage of the benefits of compact living. It should be noted that the individual model presents a more realistic estimate of energy intensities based on how people lived the United States in 2003, whereas the combined model starts with a base scenario and offers opportunities to simulate what would happen if people lived differently. Both combined models achieved a substantial improvement — better than each factor in the individual model (R^2 increased from 0.73 to 0.80.)

We use the results presented in Table 7 to investigate the differences in total energy requirements between sprawl and compact living for the two extreme scenarios while holding family size constant. For sprawl, we consider a household in an area with a population size of less than 125,000 living in a single-family home with five or more vehicles. (We decided to neglect the fact that choosing a mobile home would yield a slightly higher estimate for the extreme scenario.) This scenario was compared with compact living for the same family, but with no cars and living in an apartment in an area where the population is between 125,000 and 330,000. We find that the former household is 78% more energy intensive. However, if the two families lived in the same area, the difference would still be 60%. Table 7 offers opportunities for this type of scenario analysis for researchers and planners.

3.4. Uncertainty Analysis

There are many sources of uncertainty in our conclusions. We assume that the errors in energy intensities ($\Delta\varepsilon_i$) and expenditures (ΔY_i) are independent, and use the method of Herendeen and Tanaka (1976) to combine them.

Sources of error in energy intensities include errors in the economic input–output method itself, in the EIO-LCA method (noted by us above, and Hendrickson et al. (2006)), in estimation of transportation and trade margins from BEA data, from standard aggregation problems, and from technological changes and inflation during the ca. six years' lag in availability of national input–output data. Lenzen (2000) estimated the standard error in the input–output-based energy intensities to be about 10–20%. Based on the

Table 8
Standard errors (SE) in the estimation of annual total expenditure and annual energy requirements are shown for the average U.S. household in the sample for aggregated categories.

	Expenditure ($/yr)		Energy (MBtu/yr)	
	Estimate	SE	Estimate	SE
Total	49,261	826	604	6.5
Food/alcohol/tobacco	6211	68	38	0.4
Housing	15,276	247	75	1.3
Residential fuel	1745	18	243	2.5
Apparel	1254	34	8	0.2
Healthcare	2928	57	6	0.1
Vehicle purchase/maintenance	6855	208	38	1.4
Vehicle fuel	1466	21	138	2.0
Public transportation	423	20	9	0.4
Other	9742	243	28	0.8
Asset gain	3361	428	15	2.0

above data, we use our best judgement to assign standard errors of 10%, 20%, or 30% to the intensities of consumption categories.

Errors in expenditure values arise from non-reporting as well as variations in interviewee interpretation. We present the standard errors of the mean parameter estimates for the average household for the aggregated categories in Table 8. However, in our statistical analysis of household energy versus expenditures, we assume that the standard errors in the regression are good surrogates for uncertainty in reporting expenditures. Based on the regression of Eq. (3), the total uncertainty in total energy (E) is given by Eq. (8). Standard errors for regressions of energy on total expenditures are shown in Tables 5, 6, and 7. Results of uncertainty analysis are shown in Table 9 and Fig. 4.

$$\Delta E / E \approx \sqrt{\sum_i \left(Y_i^2 (\Delta\varepsilon_i)^2\right) \Big/ \left(\sum_i \varepsilon_i Y_i\right)^2 + (\Delta K / K)^2 + (\ln Y * \Delta\alpha)^2} \quad (8)$$

We observe that the combined fractional uncertainty ($\Delta E/E$) decreases with increasing expenditure. Considering the highest combined error (11% for the lowest income decile) to be the standard deviation of a normal probability function, we find that there is an ca. 85% probability that the rural–urban difference is positive, 67% probability that it is ≥10%, and 50% probability that it is at least 17%.

4. Discussion

The results of this cross-sectional study of U.S. households for 2003 indicate that rural households are 17% more energy intensive than urban households and households living in areas with the lowest population size (less than 125,000) are 19% more energy intensive than those living in areas with the highest population size (greater than 4 million). This takes into account the actual circumstances (bigger housing, longer commute, etc.) of people's lives. If we only consider the effect of location with all other variables being the same, the difference is about 10%. In this paper we focus on the former as it reflects actual choices made by people living in different locations. We also find that a household's percentage of direct energy use falls with increasing expenditure while the percentage of indirect energy use increases linearly with expenditure. As a result, total energy use continues to rise with increasing expenditure. Sprawl-related variables account for a large share of a household's energy budget (70–90%) at all expenditure levels.

The effects noted above are lower than the ones often reported in the sprawl literature. We offer two explanations based on our analysis. First, while it is possible to find large differences in specific case studies, nationwide data shows a smaller difference between sprawl and compact living. Even though sprawl-related energy consumption by households was large and offered great potential to reduce energy, urban households in the U.S. had not exploited that potential in 2003. Second, compact living may reduce energy intensity as a result of reduced use of direct energy, but the net energy savings were lessened because money saved on direct energy was spent on other goods and services that use energy indirectly. For example, annual energy savings from reduced automobile use can be potentially offset by the energy consumed in more frequent air travel. Holden and Norland (2005) find a positive correlation between increasing population density and longer leisure-time travel by plane. Thus, we stress that, in addition to location of residence, a more accurate estimation of the energy intensity of sprawl must consider lifestyle, consumption behavior, and many other everyday choices that people make. The linear relationship between indirect energy and total expenditure is instructive in this context.

The energy intensities presented in Table 3 can be used to assess the energy requirements of various consumer goods and services in the United States for 2003. This information is useful for individuals, planners, policy makers, and researchers who are interested in designing less energy-intensive lifestyles and communities. One point to note is that aside from the energy intensity of direct energy and public transportation, there is small variation in the energy intensity of all other non-energy categories (see Table 3). Also, the average energy intensity of direct energy is 26 times higher than average energy intensity of indirect energy. Therefore, as long as people maintain a constant expenditure level they will not make much progress in reducing their energy impact simply by shifting expenditures from one indirect energy category to another.

We develop two models that offer opportunities for further analysis. The individual model (Table 6) allows us to estimate the change in energy intensity as a result of various demographic predictors. In addition to the effects of location-dependent variables addressed here — urban/rural and population size in the area of residence — we find large differences in

Table 9
Combined uncertainty in the estimate of total energy requirements for the mean expenditure of each expenditure decile in the sample.

Decile	Total exp ('000 $)	Error in energy intensity	K	α	Total energy (MBtu)	Error in statistical regression	Combined error
1	11.51	10%	45.18	0.68	238.09	3%	11%
2	18.26	10%	45.18	0.68	325.91	4%	10%
3	23.94	9%	45.18	0.68	391.80	4%	10%
4	29.43	9%	45.18	0.68	450.94	4%	10%
5	35.58	9%	45.18	0.68	513.12	4%	9%
6	42.47	8%	45.18	0.68	578.77	4%	9%
7	50.90	8%	45.18	0.68	654.59	4%	9%
8	61.86	8%	45.18	0.68	747.47	4%	9%
9	78.28	7%	45.18	0.68	877.34	4%	8%
10	140.15	7%	45.18	0.68	1303.88	5%	8%

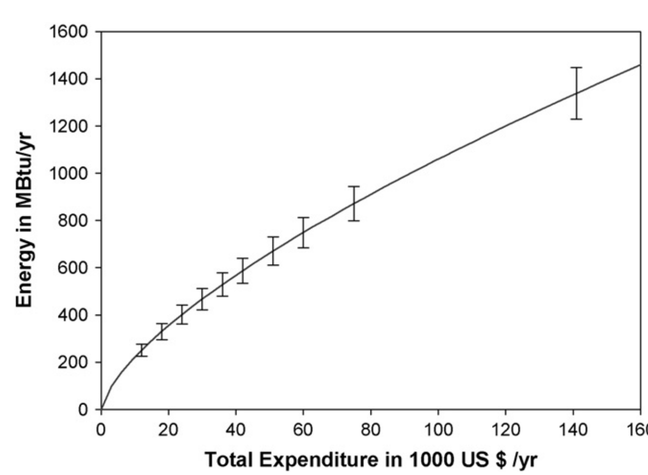

Fig. 4. The regression fit of total expenditure versus total energy requirements plotted with error bars for the mean expenditure level of each expenditure decile in the sample (2003).

energy intensities associated with variables related to lifestyle, such as choice of residence type, number of cars, and family size. The combined model (Table 7) provides more flexibility than the individual model because it allows multiple demographic predictors to be varied at the same time. Both models can tell us the change in energy intensity if people in the U.S. made different lifestyle choices in 2003. We compared two extreme scenarios using Model B in Table 7 and found that sprawl can be as much as 78% more energy intensive than compact living in the most extreme scenario. However, when we remove the effect of location we are still left with a 60% effect. While lifestyle choices are not entirely independent of the location of residence (e.g. single-family homes dominate rural and low-density locations, and lack of mass transit there means higher automobile use), this indicates that there are opportunities for households to design a significantly less energy-intensive lifestyle by making appropriate consumption and behavioral choices irrespective of where they live. In particular, the overall size of the chosen lifestyle is important, as indicated by the large effects associated with family size, number of vehicles, and building type.

Finally, we would like to stress that even though the effect of lifestyle choices can be as much as 78% and sprawl-related energy consumption can account for 70–90% of household energy consumption (83% for the average household), urban households in the U.S. in 2003 did not take full advantage of the potential opportunities for reducing energy consumption. As a result, based on how people actually lived in the U.S. in 2003, sprawl was only 17–19% more energy intensive than compact living.

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