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16. Abstract The built environment can be used to influence travel demand, but very few studies consider the relative energy savings of such policies in context of a complex urban system. This analysis quantifies the day-to-day and embodied energy consumption of four different neighborhoods in Austin, Texas, to examine how built environment variations influence various sources of urban energy consumption. A microsimulation combines models for petroleum use (from driving) and residential and commercial power and natural gas use with rigorously measured building stock and infrastructure materials quantities (to arrive at embodied energy). Results indicate that the more suburban neighborhoods, with mostly detached single-family homes, consume up to 320% more embodied energy, 150% more operational energy, and about 160% more total life-cycle energy (per capita) than a densely developed neighborhood with mostly low-rise-apartments and duplexes. Across all neighborhoods, operational energy use comprised 83 to 92% of total energy use, and transportation sources (including personal vehicles and transit, plus street, parking structure, and sidewalk infrastructure) made up 44 to 47% of the life-cycle energy demands tallied. Energy elasticity calculations across the neighborhoods suggest that increased population density and reduced residential unit size offer greatest life-cycle energy savings per capita, by reducing both operational demands from driving and home energy use, and from less embodied energy from construction. The results support the notion that transportation and the built environment are strongly linked, and improving urban energy efficiency must come from policies and designs targeting embodied sources, not just a household's travel and daily energy consumption.					
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**LIFE-CYCLE ENERGY IMPLICATIONS OF DIFFERENT RESIDENTIAL
SETTINGS: RECOGNIZING BUILDINGS, TRAVEL, AND PUBLIC
INFRASTRUCTURE**

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Land Use and Transportation Patterns

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EXECUTIVE SUMMARY

As the second largest energy consumer and greenhouse gas (GHG) emitter (behind China), the U.S. and its energy policies have large implications for global GHG emissions and the energy industry. The U.S. is seeking a (legally non-binding) GHG emissions reduction of 17% below 2005 levels by 2020 (Damassa et al. 2012), and has mentioned targets near 83% of 2005 levels by 2050 (DOE 2009). If the U.S. remains committed to these targets while accommodating growing population and urbanization, managing both transportation and the built environment will be critical focus areas: transportation is responsible for about 28% of U.S. energy consumption annually (with 60% of this share coming via personal travel [NAS 2013]), while residential and commercial buildings constitute up to 41% (NAS 2013).

While much research has considered built environment (BE) impacts on travel choices, much less research has considered impacts on buildings and infrastructure, even though buildings consume nearly 2.5 times the energy used for U.S. personal transport. Furthermore, the embodied energy of materials for constructing and maintaining buildings and other infrastructure is rarely considered alongside purported transportation energy savings from different BE designs. Thus, a more holistic energy analysis is typically overlooked, and various sectors of the urban environment (e.g., vehicles and roads, residential and commercial buildings) are too rarely compared to identify the most effective “levers” for reducing energy consumption. This approach evaluates the life-cycle energy demands of existing and theoretical neighborhoods in Austin, Texas, in a way that explicitly identifies key levers for urban energy reduction. For instance, how much total energy can be saved by increasing a given neighborhood density, and in which sectors (transportation, buildings, infrastructure) will those impacts be most critical? This analysis emphasizes a more holistic evaluation of BE variations, to better evaluate relative energy savings sources and recommend optimal focus areas, and the model introduced here allows one to better understand how land-use policies can affect energy use across different neighborhood types.

This approach requires a system of models and rigorous geographical information system (GIS) analysis to estimate building materials quantities across the distinct neighborhoods (in order to derive embodied-energy estimates). Energy use at a neighborhood scale involves many different subsystems, including buildings (homes, apartments, offices and commercial structures), roadways, sidewalks, driveways, parking structures, water and wastewater systems, municipal lighting, and more (such as natural gas pipes and electric utility infrastructure). These subsystems’ key energy requirements are estimated here via models using U.S. data sets, such as the National Household Travel Survey (NHTS) and the Residential Energy Consumption Surveys (RECS). The methodology sections of this work detail the modeling and analytical processes pursued to quantify the life-cycle energy demands of four Austin neighborhoods, and then evaluate the elasticity of (expected) energy demands with respect to various BE attributes of each location

Four distinct residential neighborhoods were selected to represent a range of neighborhood types. All come from the Austin area, in order to provide some focus and comparability, but they are general enough to have come from most U.S. urban areas. To ensure comparability in energy expenditures, the same cross-section of residential population was assumed in all neighborhoods. In this way, one controls for demographic variation and is able to evaluate

energy differences based solely on each neighborhood's BE and regional location characteristics. In this model, operational (i.e., day-to-day) energy use includes residential and commercial electricity, natural gas, water, and wastewater consumption, fuel use from personal (household-owned) light-duty vehicles (LDVs), and public street lighting. When possible, these values were estimated via behavioral models (using regression equations for vehicle ownership details, driving distances, transit use, and building energy use [per SF of building interior]), but the energy-related water and wastewater estimates rely on aggregate assumptions (from Austin, California, and Florida studies) and GIS-based tabulations (of actual infrastructure observed in the neighborhoods).

Accounting for energy consumption sources across neighborhoods offers insight into the relative impacts of different sectors across land-use styles, but does not necessarily identify how specific land-use and behavioral changes can impact total energy use. Computing elasticity values allows one to anticipate impacts from changes in model parameters. In this case, elasticities were computed to estimate how energy consumption (in operational and embodied stages, and in total) responds to specific changes in the BE or user behavior. Transportation and household energy use calculations illustrate how BE characteristics significantly influence (expected) vehicle purchases, driving choices, transit use, and heating and cooling demands. Since all neighborhoods assume a demographically uniform population, variations of per-capita impacts across neighborhoods can be attributed to population and jobs densities, housing style, and urban location (i.e., distance to Austin's CBD) and residential unit size. In reality, demographic variations may produce even greater variations across these four settings, since income, household size, number of workers, and other variables significantly impact behaviors, as indicated by model parameters.

Predictions of person-miles traveled on transit modes are also interesting, though the findings may not be practically significant for these chosen neighborhoods. In general, transit miles used per household were quite low in all four neighborhoods, which is quite consistent with Austinites' existing travel patterns. The four case neighborhoods clearly vary in their required infrastructure and (expected) travel behaviors (assuming the same set of households residing in each). Table 3 presents their overall energy consumption estimates, for operation versus embodied energy, and uses relating to transport, buildings, and infrastructure. This analysis provides a holistic approach for evaluating the long-term energy impacts of different neighborhood types, and creates some metrics that help evaluate how land-use and transportation designs and policies may impact energy use at the neighborhood level, and even higher (larger) spatial scales. By evaluating a diverse set of real-world neighborhoods, this work quantifies energy savings from different land-use patterns.

This evaluation also illuminates out how most improvements in energy efficiency must come through reduced fuel consumption and less energy-intensive transportation infrastructure, including parking facilities and roadways. In summary, there are many opportunities to improve urban energy efficiency, and thoughtful BE planning and transport policy can improve aggregate energy efficiency and reduce associated environmental, societal, and economic impacts. Taking a life-cycle perspective on energy analysis provides more context on how density and residential building styles impact total energy use. While operational energy from driving and electricity and natural gas use are the major consumption sources in neighborhoods, their estimated rates

varied significantly across neighborhood types in Austin, with the least efficient neighborhood consuming nearly twice the total energy per-capita as its most efficient counterpart. Combined with the fact that embodied energy estimates comprise between 8 and 17% of total life cycle energy, this study suggests that development patterns can have a significant impact on energy consumption rates.

DISCLAIMER

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BACKGROUND

As the second largest energy consumer and greenhouse gas (GHG) emitter (behind China), the U.S. and its energy policies have large implications for global GHG emissions and the energy industry. The U.S. is seeking a (legally non-binding) GHG emissions reduction of 17% below 2005 levels by 2020 (Damassa et al. 2012), and has mentioned targets near 83% of 2005 levels by 2050 (DOE 2009). If the U.S. remains committed to these targets while accommodating growing population and urbanization, managing both transportation and the built environment will be critical focus areas: transportation is responsible for about 28% of U.S. energy consumption annually (with 60% of this share coming via personal travel [NAS 2013]), while residential and commercial buildings constitute up to 41% (NAS 2013). Land-use policies aimed to improve energy efficiency (e.g., Smart Growth and New Urbanism) may play a critical role in reducing U.S. GHG emissions over time, while improving the nation's energy security and moderating a variety of environmental impacts.

While much research has considered built environment (BE) impacts on travel choices, much less research has considered impacts on buildings and infrastructure, even though buildings consume nearly 2.5 times the energy used for U.S. personal transport. Furthermore, the embodied energy of materials for constructing and maintaining buildings and other infrastructure is rarely considered alongside purported transportation energy savings from different BE designs. Thus, a more holistic energy analysis is typically overlooked, and various sectors of the urban environment (e.g., vehicles and roads, residential and commercial buildings) are too rarely compared to identify the most effective “levers” for reducing energy consumption. This analysis emphasizes a more holistic evaluation of BE variations, to better evaluate relative energy savings sources and recommend optimal focus areas.

Perhaps the largest volume of BE analysis considers various impacts to household travel choices. While some conclude that compact, accessible, mixed-use designs reduce driving, while promoting transit use and non-motorized travel (NMT) (e.g., Handy 1996a, Levine 1999, Bernick and Cervero 1997, Cervero and Kockelman 1997, Cervero et al. 2002, Khan et.al, 2013), others find relationships to be weak and indirect (Giuliano 1995, Krizek 2003). There is also the issue of self-selection bias (Mokhtarian and Cao 2008), which diminishes most estimates of causation (by perhaps 50 percent [Zhou and Kockelman 2008]). Smart growth practices and related built environment (BE) designs are often advertised as reducing municipal services and infrastructure costs (see, e.g., Burchell et al. 2002 Litman 2013), along with regional congestion, emissions, crashes, and various other transportation-related costs; but these impacts are rarely considered holistically, from an energy and GHG emissions perspective.

Some research efforts extend their analyses to consider impacts of urban systems through microsimulation approaches (see, e.g. Waddell et al. 2003, Maoh et al. 2005, Tirumalachetty et al. 2013, and others), but these often focus on anticipating land-use changes over time, rather than comparing energy use across BE settings. Norman et al. (2006) performed a comprehensive analysis of energy use in two distinct Toronto neighborhoods. In addition to evaluating daily transportation and household energy consumption between low- and high-density neighborhoods, they considered the impacts of embodied energy (i.e., that associated with materials manufacture, construction, and building and infrastructure maintenance). Their life-

cycle approach provided a holistic evaluation of all energy sinks across the two neighborhoods, and showed how the low-density neighborhood could be 2 to 2.5 times more energy-intensive (per capita) than the high-density neighborhood, with the embodied energy of neighborhood materials accounting for around 10% of the life-cycle energy use, transportation accounting for 20 to 30%, and building operations from 60 to 70%. Little, if any, other work provides their level of detail and scale. Importantly, their results suggest that the embodied energy and buildings consume a significant portion of a neighborhood's energy use, and should be granted more consideration in land use-transportation analyses.

Though Norman et al. (2006) performed a rigorous life-cycle analysis (LCA), their transportation and buildings energy estimates were taken from aggregate (national) estimates and no heterogeneity across households was considered, resulting in a rigid accounting framework, rather than the more flexible model pursued here, which illuminates impacts of policies changing various BE variables. The model introduced here allows one to better understand how land-use policies can affect energy use across different neighborhood types. This approach evaluates the life-cycle energy demands of existing and theoretical neighborhoods in Austin, Texas, in a way that explicitly identifies key levers for urban energy reduction. For instance, how much total energy can be saved by increasing a given neighborhood density, and in which sectors (transportation, buildings, infrastructure) will those impacts be most critical?

This approach requires a system of models and rigorous geographical information system (GIS) analysis to estimate building materials quantities across the distinct neighborhoods (in order to derive embodied-energy estimates). The following sections detail the modeling and analytical processes pursued to quantify the life-cycle energy demands of four Austin neighborhoods, and then evaluate the elasticity of (expected) energy demands with respect to various BE attributes of each location.

METHODOLOGY

Energy use at a neighborhood scale involves many different subsystems, including buildings (homes, apartments, offices and commercial structures), roadways, sidewalks, driveways, parking structures, water and wastewater systems, municipal lighting, and more (such as natural gas pipes and electric utility infrastructure). These subsystems' key energy requirements are estimated here via models using U.S. data sets, such as the National Household Travel Survey (NHTS) and the Residential Energy Consumption Surveys (RECS). Other sources, for the materials volumes of streets, sidewalks, and piped systems, for example, were estimated using GIS data from the City of Austin, coupled with satellite imagery and local codes and design standards. Table 1 summarizes the various data sources and modeling approaches used. Estimated energy requirements are separated by sector (buildings, transportation, and other infrastructure) and by use phase (operational/on-going or embodied/initial construction). Many of these models, and the sector divisions, are described in following subsections.

Table 1. Microsimulation Models and Data Sources.

<i>Sector</i>	<i>Consumption Source(s)</i>	<i>Operational Energy</i>	<i>Embodied Energy</i>	<i>Model(s)</i>	<i>Data Source(s)</i>
Buildings	Electricity Use	<input checked="" type="checkbox"/>		OLS	RECS & CBECS
Buildings	Natural Gas Use	<input checked="" type="checkbox"/>		OLS	RECS & CBECS
Buildings	Building Materials		<input checked="" type="checkbox"/>	GIS	City of Austin
Transportation	Personal Vehicles' Fuel Use	<input checked="" type="checkbox"/>		OLS, Poisson, MNL	NHTS
Transportation	Transit Fuel Use	<input checked="" type="checkbox"/>		OLS	Austin Travel
Transportation	Streets		<input checked="" type="checkbox"/>	GIS	City of Austin
Transportation	Sidewalks		<input checked="" type="checkbox"/>	GIS	City of Austin
Infrastructure	Water & Wastewater		<input checked="" type="checkbox"/>	GIS	City of Austin
Infrastructure	Water & Wastewater Use	<input checked="" type="checkbox"/>		GIS	City of Austin
Infrastructure	Street Lighting	<input checked="" type="checkbox"/>		GIS	Google Earth

Austin Neighborhoods

Four distinct residential neighborhoods were selected to represent a range of neighborhood types. All come from the Austin area, in order to provide some focus and comparability, but they are general enough to have come from most U.S. urban areas. As detailed in Table 2, these neighborhoods range from a proto-typical U.S. suburban subdivision, with curvilinear roads and cul-de-sacs (Anderson Mill [neighborhood #2]), to a very dense, low-rise multi-family apartment area (Riverside [#4]). Hyde Park (#3) offers a rather high density mix of single-family and multi-family homes, on a gridded street pattern, very near Austin’s central business district (CBD). The Westlake neighborhood (#1) represents a sprawling, wealthy neighborhood, with semi-rural character mixed in. It varies significantly from Anderson Mill (#2), in its large lots and home sizes, but greater proximity to the CBD. Table 2 characterizes these four neighborhoods while also reporting several model outputs. Neighborhoods are numbered from 1 to 4, based on density, beginning with the least dense. Each neighborhood’s geographical size reflects a census tract, or a combination of two census tracts in the case of #4 – Riverside, to include relatively similar populations, ranging from around 3,300 to 7,700 total residents. The Riverside neighborhood consists of two census tracts to ensure an equal overlap with Austin travel analysis zone (TAZ) data, which was used to derive employment data.

Table 2. Austin Neighborhood Characteristics and Summary Statistics (from GIS Analysis and Model Applications).

	<i>1 – Westlake</i>	<i>2 – Anderson Mill</i>	<i>3 – Hyde Park</i>	<i>4 – Riverside</i>
	Large-lot SFH	Newer, small SFH	Mixed SFH, MFH	Low-rise MFH
Site Attributes & Behavioral Estimates				
Total Population (Census 2010)	4,865	3,394	4,939	7,728
Total Area (mi ²)	5.06	0.64	0.86	0.50
Population Density (residents/mi ²)	962	5,277	5,713	15,401
Employment Density (employees/mi ²)	94	530	2,317	1788
% Detached SFH	93%	92%	65%	8%
Miles from Centroid to Austin CBD	4.5	13.4	2.5	2.3
Streets (centerline miles/capita)	20.5	16.9	12.1	3.6
(Directional) Sidewalks (miles/capita)	4.3	24.7	9.0	3.3
Transit Stops per mi ²	0	0	27	18
Water & Wastewater Pipes (mi/capita)	15.6	10.9	12.2	3.5
Avg. LDV VMT per HH per year	8,200	7,984	7,077	7,096
Behavioral Estimates/Outputs				
Avg. Vehicles per HH	1.69	1.68	1.27	1.04
Vehicle-Type Shares	Passenger Car	64%	63%	68%
	Van	12%	12%	11%
	SUV & CUV	18%	19%	17%
	Pickup Truck	6%	6%	3%
Avg. LDV Fuel Economy (mi/gal)	23.2	23.3	23.5	23.7
Avg. LDV Fuel Use (gal/year/HH)	849	832	584	473
Annual Transit Miles per HH	346	271	167	300
Avg. HH Electricity Use (GJ/year)	97.9	91.6	74.9	66.9
Avg. HH NG Use (GJ/year)	26.9	24.8	21.8	22.0

Note: SFH and MFH stand for single- and multi-family housing, LDV is for light-duty vehicle (cars and trucks), HH signifies household, and NG is natural gas. Miles from Centroid is Euclidean distance from centroid to downtown Austin, set at the intersection of 6th St. and Congress Ave.

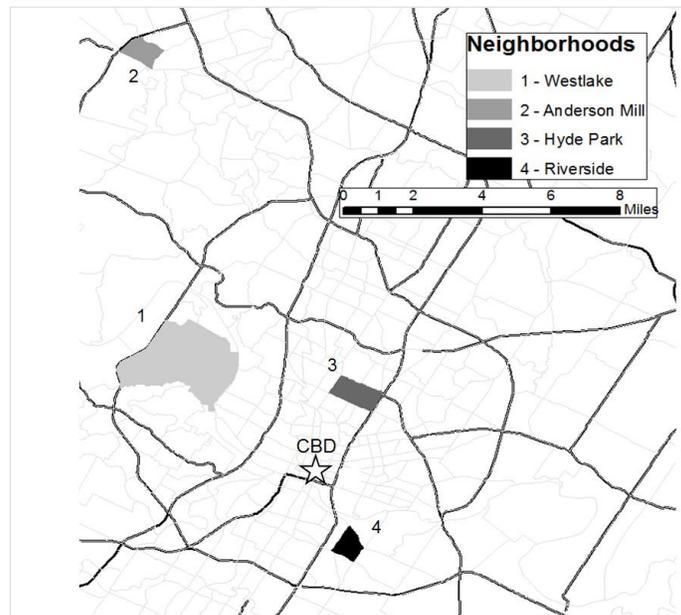


Figure 1. Map of Selected Austin, Texas Neighborhoods.

Table 2's summary and Figure 1 illuminate these residential neighborhoods' clear diversity, even within a single urban area. The settings vary dramatically, and some land-use patterns clearly demand greater travel, infrastructure provision, and energy expenditure. For instance, the number of street centerline-miles per capita is much higher for the mostly-SFH neighborhoods, especially in suburban neighborhoods 2 and 4. Water and wastewater pipe infrastructure demands (per capita) are also much greater for the lower-density developments (neighborhoods 1, 2, and 4).

Population Synthesis

To ensure comparability in energy expenditures, the same cross-section of residential population was assumed in all neighborhoods. In this way, one controls for demographic variation and is able to evaluate energy differences based solely on each neighborhood's BE and regional location characteristics. Thirty-nine different household types were considered, and distributed based on the Austin-Round Rock-San Marcos metropolitan statistical area (MSA) demographics in 2010, based on household size (1 to 4+ persons), number of workers (0 to 3+ per household), and (annual) income level (low [$< \$15,000$ per household per year], medium [$\$15,000 - \$50,000$] and high [$> \$50,000$]). Using a Public Use Microdata Sample seed for the MSA and marginal distributions on each of the 3 attributes, household shares were distributed across the 39 classes using an iterative proportional fitting procedure (see, e.g., Feinberg [1970] and Norman [1999]). For instance, results indicate that only about 2% of the area households have a combination of 4-or-more members, 3-or-more workers, and a medium income level, while 10% of area households are classified as having only one member, who is employed, and at the low-income stratification. This approach provides an approximation of the Austin area population with sufficient resolution to allow for variation within the various models, without creating an unwieldy cross-section sample.

While the mix or shares of household types is constant across the distinctive neighborhoods studied, neighborhood population and number of dwelling units vary, so all results are normalized by population (which is extracted from Census [2010] data). All dwelling units are considered 100% filled, which may be unrealistic, but represents the best case scenario when considering per-capita impacts. Additionally, average vacancy rates for rented and owned units are considerably different,¹ potentially skewing a pure energy and BE analysis.

Operational Energy Models

In this model, operational energy use includes residential and commercial electricity, natural gas, water, and wastewater consumption, fuel use from personal (household-owned) light-duty vehicles (LDVs), and public street lighting. When possible, these values were estimated via behavioral models (using regression equations for vehicle ownership details, driving distances, transit use, and building energy use [per SF of building interior]), but the energy-related water

¹ In the first quarter of 2013, average U.S. rental vacancy rates (typically associated with multi-family units) were 8.6% while average homeowner (typically single-family) vacancy was 2.1% (Census 2013).

and wastewater estimates rely on aggregate assumptions (from Austin, California, and Florida studies) and GIS-based tabulations (of actual infrastructure observed in the neighborhoods).²

Operational Energy: Transportation

Transportation energy use was estimated for LDVs and transit via fuel-use models, composed of several sub-models. This approach does not employ detailed networks and regional (zone-based) travel demand models, but rather relies on household demographics and BE characteristics to estimate the number and types of vehicles owned by each household, the number of vehicle miles traveled (VMT), and owned-vehicle fuel economies, to predict each household's annual fuel use in driving, along with the annual number of transit trips and (average) transit trip lengths.

All the LDV sub-models were estimated using the nation's 2009 NHTS data. The number of household vehicles owned (by vehicle type: passenger car, van, SUV, and pickup truck) was estimated using Poisson regression, to reflect the integer (or "count") nature of this variable. (A negative binomial model was originally specified, but a statistically insignificant dispersion parameter collapsed the model to Poisson.) Household vehicle type choice was modeled using a multinomial logit (MNL specification, generating probabilities or shares of each of the four vehicle types for each household. These probabilities were multiplied by the estimated vehicle holdings to produce the weighted average number of each vehicle owned, by household. U.S. EPA-rated fuel economy was provided in the NHTS for each vehicle (by make, model, and production year) and these values were then estimated using ordinary least squares (OLS) regression, with indicator variables for three of the four vehicle types. Household-level VMT was also estimated using OLS (while controlling for household, neighborhood, and vehicle attributes [including fuel economy, gas cost, vehicle age and type]), with all results fed into a final OLS model for each household's annual fuel use. Separating the fuel use model into multiple components allowed separate estimates for number of vehicles by type, which allowed embodied energy calculations by vehicle type.

Transit trips were modeled using the 2005/2006 Austin Travel Survey data, which is similar to the NHTS data set, but provides more information on individuals' (monthly) transit use frequency and average trip length. Two OLS models were estimated with the NHTS data: for number of transit trips per person and transit trip distances. Explanatory variables in the first of these models included household income and size, vehicle ownership, number of workers, MSA population, population and employment densities (at the block group level), distance to CBD, share of single-family homes (SFHs) in the block group, an urban location indicator, and employment status. Trip length was modeled as a function of fewer variables, including an employment status indicator, SFH share, employment density, household income, and the number of transit stops per mile in the neighborhood zone. (Population density was found statistically insignificant using a p-value threshold of 0.1.) Model predictions were scaled to the neighborhood zone level by multiplying the 39 individual results (for each neighborhood) by

² These categories represent the largest sources of urban energy use, both publically and privately, though other energy sources could certainly be included. For instance, life-cycle impacts of urban waste collection services have previously been evaluated (Iriarte et al. 2008), but are excluded in this analysis, due to data scarcity.

household size, and then household count, while reflecting the share of employed workers. Total annual energy from transit passenger miles ($E_{tr,i}$) was computed for each household i as follows:

$$E_{tr,i} = \frac{\eta}{occ} \times d_{tr,i}$$

where η is average transit vehicle efficiency (in megajoules [MJ] per vehicle-mile), occ is average bus occupancy, and $d_{tr,i}$ is total transit passenger miles traveled per household i . Here, transit vehicle efficiency is assumed to be 37.9 MJ/vehicle-mile, using an average city bus in 2010 (U.S. DOE 2012), and average bus occupancy of 10 persons, based on most recent data from Austin’s transit provider (CapMetro 2013). Bus occupancy is important for determining efficiency of passenger miles traveled, and varies across cities, and across different routes in the same city. Though occupancy might increase in urban environments, overall efficiency may be reduced with increased congestion (Kockelman et al. 2008).

Operational Energy: Residential and Commercial Buildings

Daily energy use in U.S. residential and commercial buildings included electricity and natural gas consumption, as modeled by Tirumalachetty et al. (2013) using data from the 2001 Residential Energy Consumption Survey (RECS). Tirumalachetty et al. (2013) controlled for a number of climatic, demographic, and BE explanatory variables, and used such models for an integrated transportation-land use-GHG microsimulation of the Austin region (but without as much attention paid to BE impacts and no consideration of embodied-energy impacts). Their residential energy-use models were estimated for each of the 39 household types modeled here, using the average number of children and elderly (over age 65) for the Austin-Round Rock-San Marcos MSA (Census 2010). Building-specific variables included home age, square footage, and indicators for urban versus suburban location, and single-family versus multi-family unit type. Electricity and natural gas costs (per kWh and MMBtu, respectively) were also controlled for, and relied on state average residential rates of \$0.09/kWh for electricity (EIA 2012) and \$10.90/MMBtu for natural gas (EIA 2013).

Operational Energy: Utilities

Street lighting, water, and wastewater require energy as well. Street lights constitute a costly portion of a municipality’s expenses (The Atlantic 2012), and these were noted across the four Austin neighborhoods using Google Earth satellite and Street View imagery. Each lamp was assumed to have the standard 250-watt high-pressure sodium bulb (City of Austin 2011) and operate from sunset to sunrise, or 12 hours per day, using about 3 kWh per fixture per day.

Household and commercial water use requires significant energy, for treatment and distribution (such as chlorination and pumping). Some of the consumed water is removed from the buildings and processed at a wastewater treatment plant, which requires further energy input. Detailed residential and commercial water use data are rarely collected, so aggregate estimates were assumed here. Each household was assumed to use 275 gallons of fresh water per day per household, based on City of Austin estimates (Fodor 2011). Average commercial building water use was assumed to be 0.142 gallons/ft²/day, according to studies of Florida cities (Morales and Heaney 2010). Wastewater use (for residential and commercial buildings) was assumed at 40% of freshwater use, to include only drain flows of indoor uses (e.g., dishwasher, bath, faucet,

shower, and toilet) (Mayer et al. 1999). The energy costs of water treatment, distribution, and wastewater treatment were assumed to be 1,200, 2,500, and 1,400 kWh per million-gallons, respectively, based on averages from several California systems (Klein et al. 2005). It would be desirable to separate these uses and estimate a model for each household, since water use (and associated energy demands) presumably varies across household demographics and settings, including as a function of various BE factors (Wentz and Gober 2007) and pumping distances. However, early results indicated that water-related energy use was a relatively insignificant energy draw, so such efforts are expected to be insignificant at the neighborhood scale, relative to other sources.

Embodied Energy

To estimate embodied energy impacts of urban design, this work emphasizes land uses and building types and applies a range of typical embodied-energy values per unit area (for buildings) or volume (in the case of roads and sidewalks). A more sophisticated evaluation of embodied energy may estimate volumes of all materials used in buildings (and their cost inputs) and perform a detailed economic input-output analysis (as performed by Norman et al. [2006] and developed by Hendrickson et al. [1998]) or follow a process-based analysis that traces all materials back to their manufacturing source (see, e.g., Rebitzer et al. 2004). Such approaches, however, require much time and access to data, beyond the scope of this multi-facility, whole-neighborhood investigation. Moreover, they are probably too finely detailed to provide any tangible accuracy benefits, when considering that all neighborhood structures and estimation approaches used (here, and in the competing input-output life-cycle analyses) are highly variable. This work builds off existing research and compiles results from a number of fields to estimate total embodied energy for complex urban systems and building mixes.

Building, vehicles', and materials' lifespans are a key assumption for embodied energy analysis. Here, all energy demands are annualized, and longer life-span assumptions reduce the relative impact of the embodied energy phase. When possible, well-documented lifespans were selected (as described below) and kept constant across neighborhoods for consistency. However, such numbers can vary, changing the relative roles of different neighborhood features. The following sections describe the approaches used to quantify the embodied energy requirements of buildings, other infrastructure, and structures, along with data sources used.

Embodied Energy: Infrastructure

Streets, roads, driveways, and parking lots, cover a large share of a city's surface, requiring a much concrete, asphalt, and base materials for construction and maintenance. This analysis considered neighborhoods with a range of roadway types, but mostly involved local streets and minor arterials (though some neighborhoods included sections of major arterials and highways). City of Austin GIS files provided road centerlines and classifications, and road widths were assumed to follow existing City design standards, by classification. By inspection, all roads were assumed to be asphalt topped, with depths based on anticipated average daily traffic (for each class) using AASHTO (1998) guidelines, and an optimistic lifespan of 20 years.³

³ Chester et al. (2010) used an asphalt lifespan of 10 years for parking surfaces,

Sidewalk material volumes were estimated similarly for each neighborhood, using Austin GIS centerlines, and city design standards for materials, depth, and width (City of Austin 2013). Sidewalk data files also included information on driveway entrances crossing sidewalks, which was used to extrapolate total driveway volumes, assuming an average depth and length for each neighborhood. Sidewalks were assumed to have a lifespan of 35 years (City of Dover 2006) and driveways a lifespan of 20 years (Seiders et al. 2007)

In addition to streets and sidewalks, parking lots and garages consume a great deal of land (Chester et al. 2010). Parking infrastructure energy was estimated from City of Austin land-use GIS data. Parking structure floor area was estimated from building footprint data, multiplied by the number of floors for each structure (through visual inspection). An embodied energy range of 79 to 215 MJ/ft² (depending on construction materials and technique) was applied to total floor space, based on detailed life-cycle analyses from Griffin et al. (2010) and Chester et al. (2010). Embodied energy for surface lots was calculated as for roadways, using GIS land-use data and City of Austin design parking space design standards. In some cases, GIS data excluded some private parking spaces, mostly for apartment and townhome buildings. These additional spaces were estimated using City parking requirements (one parking space required for single-bedroom units, and 0.5 spaces required for each additional bedroom per unit).

Embodied Energy: Residential and Commercial Buildings

Life-cycle analyses include a great deal of uncertainty, even when analyzing just one material or structure. Since this paper's LCA approach evaluates multiple materials and building types, each with unique construction techniques and input sources, it becomes very difficult to ensure accuracy and precision (Lloyd and Ries 2008). However, general estimates of average energy consumption still provide a useful metric when held constant across several different neighborhood types. Therefore, this analysis assumes an average rate of embodied energy per square foot, by building type. Building type and base footprint were collected for each of the four neighborhoods using Google Earth data, and total built area (per building) came from visual inspection of the number of stories per building, using Google's StreetView imagery. Embodied energy was assumed to be 0.5 GJ/ft² for single-family homes and 0.6 GJ/ft² for multi-family homes, based on an analysis by Hammond and Jones (2010). The final components considered for embodied infrastructure impacts are water and wastewater pipes. Their locations, materials, and diameters are available through the City of Austin⁴, and were tabulated for each neighborhood. Pipe material lifespan are based on estimates by Seiders et al. (2007).

Travel Demand's Energy Elasticities

Accounting for energy consumption sources across neighborhoods offers insight into the relative impacts of different sectors across land-use styles, but does not necessarily identify how specific land-use and behavioral changes can impact total energy use. Computing elasticity values allows one to anticipate impacts from changes in model parameters. In this case, elasticities were computed to estimate how energy consumption responds to specific changes in the BE or user behavior. Elasticity values have been very informative for identifying impacts of BE changes on

⁴ The City of Austin provides a large amount of GIS data at ftp://ftp.ci.austin.tx.us/GIS-Data/Regional/coa_gis.html. Water and wastewater data was made available upon email request.

travel demand, but such analyses rarely extend to include holistic energy impacts. For instance, Ewing and Cervero (2010) reviewed nearly 200 studies to compute weighted-average elasticities for vehicle miles traveled (VMT), NMT, and transit responses to changes in BE variables, but it is often unclear exactly how these impacts affect total energy. Especially important here is the phase under which impacts might occur (operational or embodied). For instance, increasing density may reduce VMT and therefore reduce operational demands, but will also decrease per-capita embodied energy demands. Understanding the individual sources and aggregate impacts of life-cycle energy savings becomes an informative extension of elasticity analysis.

Wherever possible, new “energy elasticities” were computed here, by changing BE variables used directly by the LCA model, such as population and jobs density, SFH shares, residential unit size, building age, gasoline price, and bus occupancy. The effects of some other important BE metrics (not directly computed for each neighborhood), such as land-use mix and regional accessibility, were also considered here, by simply pivoting off VMT percentage changes (using Ewing and Cervero estimates [2010]), after assuming a base/reference (accessibility or mix) value for each neighborhood.

Overall, separate elasticities ($\eta_{i,j}$) were computed for each energy “phase” i (operational, embodied, or total life-cycle energy), for several BE variables (x), via the following equation:

$$\eta_{i,x} = \left| \frac{\Delta E_i}{\Delta x} \times \frac{x}{E_i} \right|$$

where E_i is the energy use for phase i . The resulting energy elasticities provide context for how much transportation, land use, and home efficiency policies and programs fare, across neighborhoods. They allow one to extend earlier, context-specific evaluations (e.g., of BE attributes on VMT) to larger-scale energy analyses.

RESULTS AND DISCUSSION

Transportation and household energy use calculations illustrate how BE characteristics significantly influence (expected) vehicle purchases, driving choices, transit use, and heating and cooling demands. Since all neighborhoods assume a demographically uniform population, variations of per-capita impacts across neighborhoods can be attributed to population and jobs densities, housing style, and urban location (i.e., distance to Austin's CBD) and residential unit size. In reality, demographic variations may produce even greater variations across these four settings, since income, household size, number of workers, and other variables significantly impact behaviors, as indicated by model parameters.

Average households from the two suburban neighborhoods (#1 and 2) are expected to drive more miles, own more vehicles, and purchase more SUVs or CUVs, trucks, and vans, than passenger cars. Average fuel economy is relatively constant across neighborhoods due to a lack of BE-sensitive variables in the fuel economy OLS model.⁵ The households' LDV energy use levels come directly from a fuel-use model (total gallons, based on household VMT and fuel economy in the NHTS data set), which, as expected, predicts the largest per-household gasoline consumption for Westlake (#1), followed closely by Anderson Mill (#2). Essentially, fewer miles driven, fewer vehicles owned in general, and a lower concentration of lower-fuel-economy vehicles (vans, SUVs, and trucks) are associated with the higher density neighborhood (Riverside – #4) and the mixed SFH/MFH units (Hyde Park – #3).

Predictions of person-miles traveled on transit modes are also interesting, though the findings may not be practically significant for these chosen neighborhoods. In general, transit miles used per household were quite low in all four neighborhoods, which is quite consistent with Austinites' existing travel patterns. The behaviorally-based regression models for transit use suggest that the suburban neighborhoods of Anderson Mill (#2) and Westlake (#1) will generate nearly the same number of transit-trip-miles as Riverside (#4) – and more than those in Hyde Park (#3). Due to the greater distances, suburban travelers with fewer stop options per square mile, end up experiencing longer transit trips (according to the NHTS data sets, *ceteris paribus*), when they do take transit. Thus, despite a lower *number* of transit trips per household or per capita in these suburban areas (neighborhoods 2 and 4), their longer trip lengths largely equalize the total number of passenger miles traveled (PMT) by transit. In reality, Austin's Capital Metro transit coverage does not actually include the Anderson Mill (#2) neighborhood (so transit miles there are zero) and is very sparse in the Westlake (#1) area, and actual ridership will be even lower for residents of these neighborhoods.

The four case neighborhoods clearly vary in their required infrastructure and (expected) travel behaviors (assuming the same set of households residing in each). Table 3 presents their overall energy consumption estimates, for operation versus embodied energy, and uses relating to transport, buildings, and infrastructure.

⁵ BE variables from NHTS data (e.g., population, housing, and employment density, urban setting, rented vs. owned home shares) were found to be insignificant well beyond p-values of 0.1.

Table 3. Life-Cycle Energy Estimates for Four Austin Neighborhoods (GJ/year/capita)

		<i>Operational Energy</i>				<i>Embodied Energy</i>				<i>Total Life-Cycle Energy</i>			
		<i>1 -WL</i>	<i>2 -AM</i>	<i>3 -HP</i>	<i>4 -RS</i>	<i>1 -WL</i>	<i>2 -AM</i>	<i>3 -HP</i>	<i>4 -RS</i>	<i>1 -WL</i>	<i>2 -AM</i>	<i>3 -HP</i>	<i>4 -RS</i>
Transport Sources	LDV Fuel Use	45.85	40.17	31.55	25.59	--	--	--	--	45.85	40.17	31.55	25.59
	Transit Fuel Use	0.34	0.41	0.25	0.29	--	--	--	--	0.34	0.41	0.25	0.29
	Parking Garages	--	--	--	--	0.00	0.00	0.07	0.00	0.00	0.00	0.07	0.00
	Surface Parking	--	--	--	--	0.00	0.00	0.44	1.17	0.00	0.00	0.44	1.17
	Sidewalks	--	--	--	--	0.04	0.30	0.10	.03	0.04	0.30	0.10	0.03
	Streets and Roads	--	--	--	--	6.32	9.18	5.91	2.20	6.32	9.18	5.91	2.20
Building Sources	Res. – SFH	51.24	47.79	39.73	34.89	10.19	8.17	3.80	0.22	61.43	55.96	43.53	35.11
	Res. – Duplex					0.03	0.00	0.18	0.04	0.03	0.00	0.18	0.04
	Res. – Apt.					0.51	0.78	0.97	1.54	0.51	0.78	0.97	1.54
	Office/Commercial	0.00	1.59	9.23	3.04	0.00	1.61	3.59	2.85	0.00	3.2	12.82	5.89
Infrastructure Sources	Freshwater	0.15	0.15	0.15	0.15	0.25	0.21	0.19	0.22	0.4	0.36	0.34	0.37
	Wastewater	0.21	0.21	0.21	0.21	0.10	0.10	0.14	0.02	0.31	0.31	0.35	0.23
	Lighting	0.12	0.09	0.03	0.02	--	--	--	--	0.12	0.09	0.03	0.02
Transport	Sub-Total	46.19	40.58	31.8	25.88	6.36	9.48	6.52	3.4	52.55	50.06	38.32	29.28
Buildings	Sub-Total	51.24	47.79	39.73	34.89	10.73	8.95	4.95	1.8	61.97	56.74	44.68	36.69
Infrastructure	Sub-Total	0.48	2.04	9.62	3.42	0.35	1.92	3.92	3.09	0.83	0.76	0.72	0.62
Grand Total		97.91	90.41	81.15	64.19	17.44	20.35	15.39	8.29	115.35	110.76	96.54	72.48

Note: WL stands for Westlake, AM for Anderson Mill, HP stands for the Hyde Park neighborhood, and RS for Riverside.

The final rows of Table 3, and the bars in Figure 2, show how the majority (83 to 92%) of annual energy requirements can be attributed to a setting’s operational demands, such as driving and home energy use. Table 3’s columns also show how the suburban neighborhoods (Westlake and Anderson Mill, #1 and #2) require the most energy per capita, in terms of individual operational and embodied demands, and overall life-cycle uses.

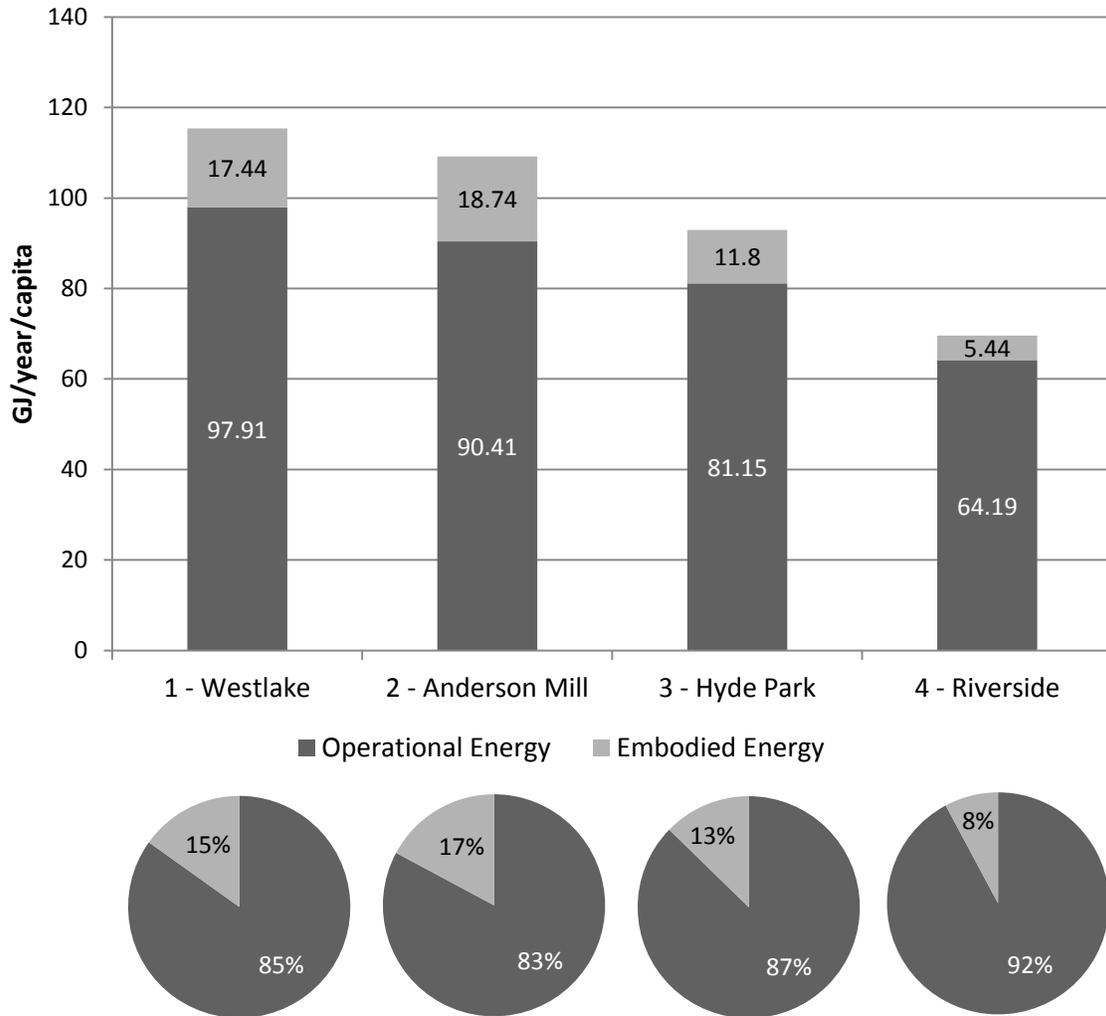


Figure 2. Comparing Energy-Use Stages Across Neighborhoods.

Separating total impacts by source illuminates the relative magnitude of transportation sources, versus buildings and other infrastructure (namely water, wastewater and municipal lighting). Figure 3 shows how annual fuel use for personal transport, along with embodied energy required to build and maintain streets, sidewalks, driveways, surface parking, and parking structures, can comprise from 40 to 46% of total life-cycle energy across these neighborhoods. Building energy use, for heating, cooling, appliances, electronics, and other uses, along with embodied energy for building materials and construction and maintenance, comprise nearly “all” the remaining portion of life-cycle energy use by these settings’ residents: roughly 53 to 55% of the totals computed here, across all four neighborhood cases. The remaining uses (water usage,

water and wastewater pipes, and lighting) may represent a significant municipal cost, but appear insignificant in these residential contexts. Of course, this analysis ignores these households' energy demands while at work, school, the gym, and other settings; while traveling by air or boat; and when consuming clothing, food, and other goods, for example. But these other expenditures are expected to be quite comparable across these same households. Additionally, this analysis does exclude other urban energy use from commercial, office, and government and or educational buildings, along with commercial and industrial shipping and other energy demands. The share of these buildings types varies across neighborhoods surveyed here, so they were excluded to maintain consistency. However, jobs-housing mix does impact travel behavior (Cervero 1989, Kockelman 1997) and therefore transportation energy, so some of these effects are not captured.

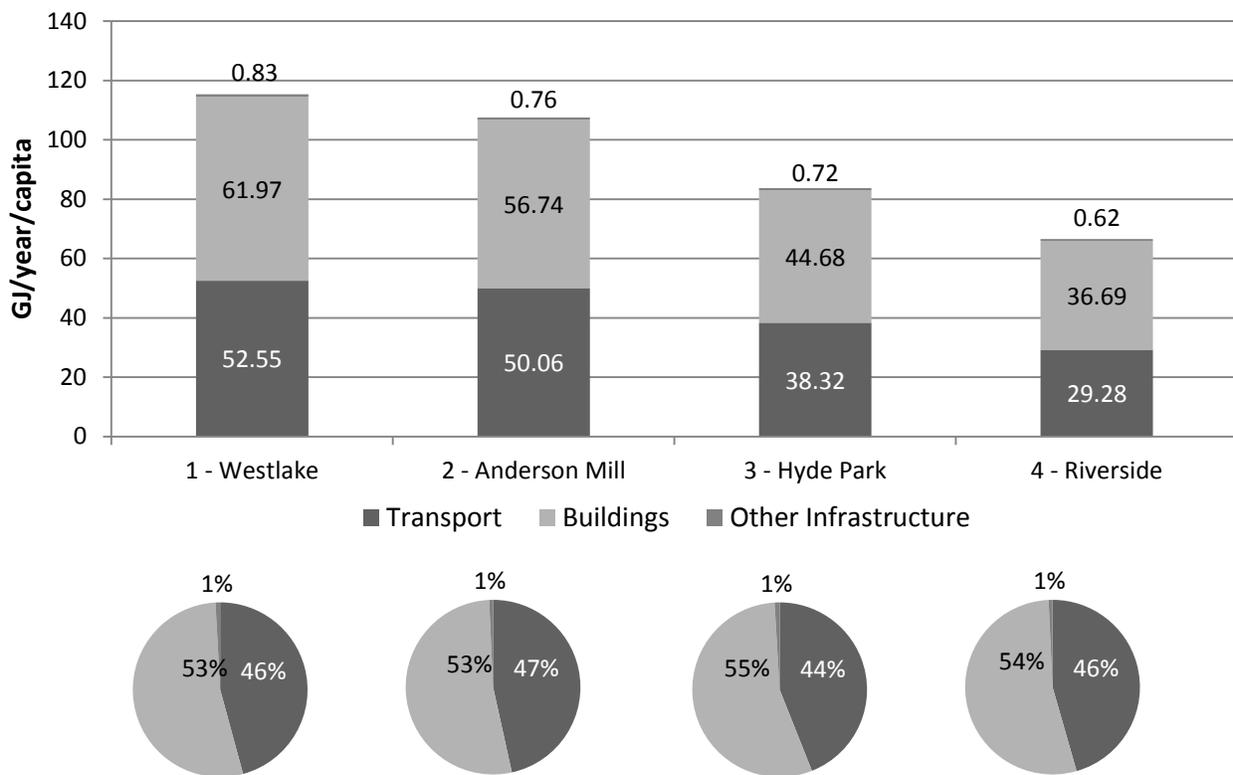


Figure 3. Life-Cycle Energy Use by Sector

While it is informative to quantify and compare the sources of life-cycle energy use across existing neighborhoods, it is even more important to consider which energy-saving strategies could best be implemented. For instance, reducing LDV fuel use and home energy consumption may be logical targets, but it is often unclear which strategies are most cost-effective. This work facilitates such analyses, by exploring (model-predicted) energy use changes, following changes in various BE characteristics (via the energy elasticities described earlier). Table 4 reports the

resulting elasticities for variables considered directly in the behavioral sub-models, along with some other important BE metrics (like regional accessibility and land use mix). The first set of elasticity values corresponds to model-integrated variables that can impact vehicle ownership, VMT, home energy use, and/or the amount of residential structures and infrastructure (for embodied energy calculations). The latter set relies on VMT- specific elasticities from Ewing and Cervero (2010).

Table 4. Energy Elasticity Calculations for Four Austin Neighborhoods.

	<i>Operational Energy</i>				<i>Embodied Energy</i>				<i>Total Life-Cycle Energy</i>				<i>VMT Elasticity</i>
	<i>1-WL</i>	<i>2-AM</i>	<i>3-HP</i>	<i>4-RS</i>	<i>1-WL</i>	<i>2-AM</i>	<i>3-HP</i>	<i>4-RS</i>	<i>1-WL</i>	<i>2-AM</i>	<i>3-HP</i>	<i>4-RS</i>	
<i>Directly Modeled Variables</i>													
<i>Population Density</i>	-0.01	-0.03	-0.19	-0.09	-0.91	-0.77	-0.58	-0.60	-0.24	-0.14	-0.25	-0.21	--
<i>Housing Unit Density</i>	-0.00	-0.03	-0.06	-0.14	+0.01	+0.03	+0.03	+0.09	0.00	-0.02	-0.04	-0.09	--
<i>Employment Density</i>	-0.02	-0.01	-0.03	-0.02	0.00	0.00	0.00	0.00	-0.01	0.00	-0.01	-0.02	--
<i>% Residential SFH</i>	-0.01	-0.01	-0.02	0.00	+0.62	+0.49	+0.29	+0.03	+0.29	+0.08	+0.04	0.00	--
<i>Resid. Building Age</i>	+0.05	+0.05	+0.05	+0.04	0.00	0.00	0.00	0.00	+0.03	+0.04	+0.03	+0.03	--
<i>Resid. Unit Size</i>	+0.12	+0.08	+0.05	+0.06	+0.56	+0.53	+0.40	+0.47	+0.29	+0.25	+0.21	+0.18	--
<i>Gasoline Price</i>	-0.04	-0.04	-0.04	-0.06	0.00	0.00	0.00	0.00	-0.02	-0.04	-0.03	-0.05	--
<i>Avg. Bus Occupancy</i>	0.00	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	--
<i>Other BE Variables</i>													
<i>Land Use Mix</i>	-0.02	-0.02	-0.02	-0.02	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.02	-0.09
<i>% 4-way Intersections</i>	-0.03	-0.03	-0.02	-0.03	0.00	0.00	0.00	0.00	-0.02	-0.02	-0.01	-0.02	-0.12
<i>Job Accessibility (via auto)</i>	-0.05	-0.05	-0.04	-0.05	0.00	0.00	0.00	0.00	-0.03	-0.03	-0.02	-0.04	-0.20
<i>Job Accessibility (transit)</i>	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.05
<i>Distance to CBD</i>	-0.05	-0.06	-0.04	-0.06	0.00	0.00	0.00	0.00	-0.03	-0.04	-0.02	-0.04	-0.22
<i>Transit Stop Accessibility</i>	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.01	-0.01	0.00	-0.01	-0.05

Note: Elasticities of greatest practical significance (exceeding +/- 0.05) are bolded, and their corresponding variable names italicized.

Table 4's values are useful for identifying which design and policy parameters have greatest influence over energy use, by neighborhood type, and across operational or embodied sources. It seems that embodied energy is greatly affected by population density, resulting in very sizable overall life-cycle energy impacts. Similarly, average living space increases day-to-day energy consumption, but it is this variable's embodied energy impacts (associated with more building materials) that have the greatest impact on total energy expenditures. Together, these two variables, Population Density and Residential Unit Size, are estimated to have the greatest practical impacts on energy use, in terms of average elasticities, across a wide variety of residential settings.

In some other cases, embodied energy impacts are negligible. For instance, higher gasoline prices and bus occupancy levels offer slight savings in operating-energy use, but have lower elasticities for overall energy use after incorporating their assumed non-existent embodied-energy impacts. Such moderate impacts also emerge for the indirectly estimated, VMT-based changes. Elasticity estimates for this latter set of neighborhood attributes presumes that their changing does not impact infrastructure design and embodied energy levels; in reality, however, increased job accessibility and rising land use mix are likely to come with increases in density and smaller residential units (and less commercial space per worker, for example). The elasticities computed here suggest that by doubling, for instance, job accessibility by automobile, the resulting (estimated) 20% decrease in VMT may provide a 4% (operational) energy use savings and total (life-cycle) savings of roughly 2%, for a specific neighborhood. To better reflect the marginal impacts of these VMT-focused BE variables, a study that quantifies each neighborhood's accessibility, mix, and other attributes, and then controls for these in one or more of the LCA sub-models is needed. Such studies may find greater (marginal) impacts (holding all other variables constant). It also is likely that the variables of population (and jobs) density, %Residential SFH, and Residential Unit Size are partly proxying for facets of these other BE variables, so these important model inputs' impacts (and elasticities) will probably diminish once more BE attributes are controlled for, in the behavioral sub-models.

CONCLUSIONS

This analysis provides a holistic approach for evaluating the long-term energy impacts of different neighborhood types, and creates some metrics that help evaluate how land-use and transportation designs and policies may impact energy use at the neighborhood level, and even higher (larger) spatial scales. By evaluating a diverse set of real-world neighborhoods, this work quantifies energy savings from different land-use patterns. While some of the results developed here may best apply to only the four Austin neighborhoods evaluated, it is likely that most (if not all) of the general trends uncovered here can be extrapolated to other cities and settings. Certainly, the methods, model framework, and metrics used here can be employed elsewhere. This work's major achievement lies in disentangling a complex set of urban subsystems and compiling energy estimates via interconnected models and careful visual and GIS analysis. This work provides a framework for evaluating new and existing neighborhoods – of any kind, making extensions a natural possibility.

Most energy-reduction policies focus on reducing VMT or improving building efficiencies, but this analysis shows that between 8 and 17% of life-cycle energy can be attributed to the BE's embodied energy impacts in the four residential neighborhoods examined here. These more compact, higher-density developments provide opportunities to reduce *both* VMT (and thus transportation's energy demands) *and* embodied energy. In the most extreme case, the traditional suburban neighborhood examined here (Anderson Mill, #2) required up to 3.2 times the embodied energy (per capita) of the densest neighborhood (Riverside, #4) and 1.6 times its total (life-cycle) energy. Even if Neighborhood 2's operational energy demands were to remain constant, changing its BE attributes to match those of Neighborhood 4 (Riverside), could reduce annual total energy use by nearly 5%, simply by reducing embodied energy demands. Such energy savings are not easy to estimate, and this analysis offers a more holistic view of how neighborhood design can impact energy consumption.

Energy elasticity calculations suggest that changes in two important BE variables, population density and residential unit size, can trigger the greatest per capita energy savings. These are critical policy variables that can be used to drive energy efficiency in future developments by way of astute planning and zoning policy, and municipal infrastructure investments that align with density and sizing goals. Density and unit sizing are the most energy-responsive BE variables in this analysis, and should be regarded as one of the most efficient approaches in reducing life-cycle urban energy use.

This evaluation also illuminates out how most improvements in energy efficiency must come through reduced fuel consumption and less energy-intensive transportation infrastructure, including parking facilities and roadways. Altogether, fuel use and transportation infrastructure comprised around 45% of life-cycle energy demands across the distinctive residential neighborhoods examined here (both real and simulated/extrapolated [for elasticity computations]). Since per-capita VMT in the U.S. has been falling recently and vehicle fuel economies are improving (thanks to rising Corporate Average Fuel Economy standards), such a statistic is rather encouraging, since it indicates reachable goals of energy reductions in the near future.

In summary, there are many opportunities to improve urban energy efficiency, and thoughtful BE planning and transport policy can improve aggregate energy efficiency and reduce associated environmental, societal, and economic impacts. Taking a life-cycle perspective on energy analysis provides more context on how density and residential building styles impact total energy use. While operational energy from driving and electricity and natural gas use are the major consumption sources in neighborhoods, their estimated rates varied significantly across neighborhood types in Austin, with the least efficient neighborhood consuming nearly twice the total energy per-capita as its most efficient counterpart. Combined with the fact that embodied energy estimates comprise between 8 and 17% of total life cycle energy, this study suggests that development patterns can have a significant impact on energy consumption rates.

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