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Life-cycle energy implications of different residential settings: Recognizing buildings, travel, and public infrastructure

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HIGHLIGHTS

- Total energy demands (operational & embodied) of 5 Austin settings were studied here.
- Suburban settings consume much more energy than densely developed neighborhoods.
- Transportation sources make up 44 to 47% of the total energy demands tallied.
- Operational energy use comprised 83–92% of total energy use in these neighborhoods.
- Higher population densities & smaller residential units offer greatest energy savings.

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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. These results provide measurable metrics for comparing different neighborhood styles and develop a framework to anticipate energy-savings from changes in the built environment versus household energy efficiency.

1. Introduction

As the second largest energy consumer and greenhouse gas (GHG) emitter (behind China), U.S. energy policy has 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 alone is responsible for about 28% of total U.S. energy consumption annually (with 60% of this share coming from personal travel (NAS, 2013)), and residential and commercial buildings consume up to 41% of all the nation's energy every year (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 (see, e.g., Handy (1996a), Levine (1999),

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Bernick and Cervero (1997), Cervero and Kockelman (1997), Cervero et al. (2002), Khan et al. (2014)), 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.

Together, the day-to-day (operational) and embodied phases of specific materials or structures have been rather heavily researched (though much uncertainty surrounds the analyses) within the field of life-cycle analysis (LCA). LCA provides an appropriately holistic perspective on total energy (or emissions) associated with many of the urban environment′s "building blocks," but very few studies have attempted to aggregate micro-scaled LCAs to a neighborhood or regional level. Many studies trace energy pathways only for distinct materials (e.g., Hammond and Jones, 2010) or single structures—like single-family homes (e.g., Keolian et al., 2001) or various commercial building types (e.g., Junnila et al., 2006; Fay et al., 2000). By comparing low- and high-density neighborhoods in Toronto, Norman et al. (2006) provided one of the only neighborhood-level LCA perspectives. 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 LCA 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.

For the most part, studies of the built environment′s influence on vehicle-miles traveled (VMT), building energy used, and downstream emissions have been at a microscopic level, and have included only one or two measures of land use patterns. The result is a piecemeal image of how energy consumption varies across specific settings, with little perspective on the "big picture", or how urban planning influences energy at a city level, and whether any of that really matters, at a larger scale. For instance, in a meta-analysis of travel choices vis-a-vis built environment variables, Ewing and Cervero (2010) suggest that VMT has an average elasticity of around -0.09 with respect to land use diversity (indicating that a doubling in land use diversity tends to be associated with a nine-percent reduction in average VMT). While useful, it is not clear how a nine-percent reduction in driving really impacts a region′s overall energy use. When accommodating thousands and millions of new people, it is unclear whether or not land-use diversity will impact urban energy demand to the same degree as other factors, like building design and vehicle technology.

This study expands on Norman et al. (2006) work by introducing a more flexible energy modeling framework, more detailed statistical modeling, and a larger sample of case studies. By quantifying holistic energy demands for residents and workers in different urban settings, this work identifies how density patterns influence aggregate energy consumption. The analysis incorporates "building blocks" from different disciplines (travel demand, building design, infrastructure energy and LCA) to construct larger neighborhoods. Energy use estimates, by source and phase, are evaluated and compared to infer the impact of the built environment on large-scale energy demands.

2. Methods

This work develops a system of statistical models, energy equations, and estimates to capture "life-cycle" energy use across different neighborhoods. The approach captures not only energy used to heat and cool buildings and power personal vehicles, but also the "hidden" or "embodied" energy required to produce, manufacture, fabricate, and construct building materials and infrastructure components that support modern households. A combination of statistical models, point estimates (based on meta-analysis of literature), and GIS data were used to compare four Austin, Texas neighborhoods across different energy use sectors and life-cycle phases (i.e., embodied versus operational). Each analysis component is discussed below, separated first by phase, then by sector (e.g., residential buildings, personal transportation, and infrastructure). A diverse set of models and data sources were used to produce equations for each sector and phase, as summarized in Table 1, and described in detail in each subsection.

Table 1
Microsimulation models and data sources.

Sector	*Consumption source(s)*	*Operational energy*	*Embodied energy*	*Model(s)*	*Data source(s)*
Buildings	Electricity use	☑		OLS	RECS & CBECS
Buildings	Natural gas use	☑		OLS	RECS & CBECS
Buildings	Building materials		☑	GIS	City of Austin
Transportation	Personal vehicles' fuel use	☑		OLS, Poisson, MNL	NHTS
Transportation	Transit fuel use	☑		OLS	Austin travel survey
Transportation	Streets		☑	GIS	City of Austin
Transportation	Sidewalks		☑	GIS	City of Austin
Infrastructure	Water & wastewater		☑	GIS	City of Austin
Infrastructure	Water & wastewater Use	☑		GIS	City of Austin
Infrastructure	Street lighting	☑		GIS	Google Earth