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Impact of urban form on energy use in central city and suburban neighborhoods: Lessons from the Phoenix metropolitan region

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Abstract

Urban form, land use patterns, and the type of structures significantly influence a city's energy needs, and consequently, its greenhouse gas (GHG) emissions. This study aims to clarify connections between urban form and its use together with the associated energy demands for infrastructure (buildings and paved surfaces) and transport. The model is tested through case studies of two Phoenix sub-areas, one in downtown Phoenix, which is undergoing redevelopment towards higher density housing and the second, a low-density suburban area at the edge of Phoenix, which has undergone significant growth in the last two decades. The results indicate that older inner city areas continue to have the lowest energy demands and carbon emissions per capita compared to other neighborhoods examined. The low-density areas in the inner city and in the newer suburbs have almost equal amounts of energy demands per capita. However, the bulk of the energy demands in the newer suburbs is related to the transportation infrastructure while the older low-density neighborhoods have higher energy intensive residential structures.

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Keywords: urbanism; urban form; sustainability; energy; greenhouse gas; neighborhood; urban planning

1. Introduction

While the relationship between urban form and energy use in transportation has been well studied, we know far less about the impact of urban form on residential energy demands. A 2009 study commissioned by the National Academy concluded that increasing development densities does lead to modest savings in energy use in transportation, and by extension, a reduction in greenhouse gas emissions [1]. Yet, if our interest is in building energy efficient communities, a more comprehensive set of attributes need to be examined to determine whether increasing development densities actually lead to energy savings. The issue of density is especially relevant if we consider that different types of building systems have different life-cycle energy demands -- from embedded energy in materials, to construction energy, and to operational energy use during the lifetime of the buildings. Additionally, different neighborhoods with different densities and types of buildings necessitate specific forms of infrastructure services. In particular, the density and arrangement of buildings will determine the street network as well as the neighborhood's mobility choices. The focus of this study is to examine such differences in energy intensity and GHG emissions between low density and high-density neighborhoods, built near the urban core, and at the fringes of a metropolitan area.

The case study sites for this investigation are carefully chosen to reflect the changes triggered by increasing suburbanization in metropolitan regions in the US. Between 2000 and 2010, the growth of suburbs has been outpacing the growth of cities by a factor of 3 [2]. Although suburban growth has somewhat slowed in the recent years, the

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absolute numbers of new households in the suburbs continues to be substantially higher than in the city proper. Suburbs are known to typically consist of low-density single-family detached units in sprawled neighborhoods that offer few transportation alternatives other than the automobile. In contrast, central city residential areas, in general, include higher density housing mixed with other forms of land uses. The central city neighborhoods also enjoy better connectivity of the street network and access to other modes of travel, including active modes, such as walking and bicycling. While it is clear from several studies that differences between suburbs and central city areas are reflected in differences in travel energy use, few, if any have looked at the specific contribution of urban form characteristics that affect energy use in these areas. To address this gap in the literature, we examine the following question in this paper: Are suburban areas more energy intensive than central city areas after controlling for density of residential development?

This study offers an empirical assessment of life-cycle energy use in residential buildings and in neighborhood streets for four different neighborhoods in the Phoenix metropolitan region. These neighborhoods are selected to represent the variation in urban form types based on density and location within the region. The objective is to determine which urban form characteristics among the dimensions considered are most relevant in determining the energy intensity of that neighborhood.

2. Literature review

The link between transportation, energy use, and urban density has been explored extensively [3-6]. However, overall energy use in an urban area is contingent upon a larger set of built environment factors other than density of development and transportation. In particular, few studies of urban energy demands have combined embedded energy in buildings and infrastructure with operational energy required to use and maintain them. Even fewer include energy use in transportation together with the total portfolio of energy used in buildings and infrastructure to provide a complete representation of energy use within a defined urban area. In our search we were only able to identify two studies that offered a more holistic assessment of energy demands of different types of urban areas defined by factors such as density, housing type, type of street network, distance to city centers, among others [7-8].

Norman et al (2006) and Nichols and Kocklelman (2014) have taken a comprehensive approach to quantifying urban energy demands at the neighborhood level by including both embedded energy in materials and construction, as well as operational energy use in buildings and transportation. Yet, the studies use different approaches and different functional units to create the portfolio of energy demands. Norman et al (2006) compared high and low density urban areas in Toronto, assessing life cycle energy of building construction, operation and transportation. They concluded that the embodied energy and GHG emissions from the materials production were about 2.5 times higher for the low density residential area than for high density on a per capita basis, and that the high density building was 1.25 times more energy and GHG emission intensive than low-density on a unit of area basis. The embodied energy in materials and construction, which accounted for 10 percent of total life-cycle energy in their study, was evaluated with the help of an economic input-output assessment of the embedded materials in the built environment (EIO-LCA).

Instead of conducting detailed analysis of all materials used in construction (such as in EIO-LCA mentioned above), the study by Nichols and Kockleman used a combination of statistical analysis and normalized values from the literature to compare four Austin, Texas neighborhoods. These neighborhoods represented different densities and land use characteristics of residential development. This study broke new ground by including a more comprehensive set of amenities in its portfolio of neighborhood life-cycle energy such as street lighting, sidewalks, water and wastewater infrastructure. Estimates of embedded energy, which range between 8 and 17 percent of total, are in line with Norman et al.'s findings, especially given the expanded set of infrastructural services included. However, transportation energy, accounting for about 45 percent, was found to be somewhat higher as a percentage of total neighborhood energy compared to the earlier study. This could be attributed to the differences in travel behavior of households in Toronto and Austin, Texas. Regardless of these differences, the finding that low-density developments are several times more energy intensive than higher density environments is consistent in both studies.

In the context of this prior literature, this work extends the analysis of urban form impacts on neighborhood energy use by examining four distinct neighborhood types in Phoenix, Arizona. It takes a comprehensive approach similar to the study by Norman et al. (2006) but with expanded set of neighborhoods with larger boundaries defined by one or more transport analysis zones (TAZs). It uses parameters derived in Frijia et al. (2012) [9] to estimate single-family residential life cycle energy for Phoenix. The objective is to provide better understanding of how the embodied energy in roads and single-family homes play out in neighborhoods characterized by density and location within the Phoenix metropolitan area.

3. Case study area

The Phoenix Metropolitan Area (MSA) was chosen due to its pattern of rapid population growth that spurred fast, extensive, and high-density single-family residential developments; as well as for the availability of sufficiently detailed data to complete the intended analysis. The 2010 U.S. Census indicates that during the previous ten years, the Phoenix MSA grew 28.9 percent, from 3.2 to 4.2 million residents. However, some communities grew at a much faster pace. For example, the population of the Town of Buckeye, Town of Surprise, and Town of Gilbert grew 678 percent, 281 percent, and 90 percent respectively (Census 2010a). The demand for new housing units, supported by the high population growth, was met in part by large-scale tract developments of master planned single–family housing units. Specifically, in the period between 2000 and 2010 more than 327,000 new single–family building permits were issued in the Phoenix MSA (U.S. Census, 2010b).

Another important period of intense development occurred post World War II, between 1945-1960, during which the City of Phoenix incorporated most of its current land mass and quadrupled in size (Konig 1982). It was towards the end of this period, in the late '50s that the first modern master planned communities appeared in Arizona (i.e., the J.F. Long residential developments in Maryvale in the late '50s, and the development of the "McCormick Ranch" in the mid '60s, in the heart of Scottsdale).

For this study it was important to capture some of the difference in planning, development styles, street layout and characteristics (i.e., cul-de-sacs, offset alignments) that have shaped the Phoenix MSA urban environment during the past housing booms. This was done by first delineating two study areas, one in the central part of Phoenix and another in the suburban city of Gilbert. This was accomplished by using four selection criteria:

1. The areas should include both new large master planned communities developed by a single builder, over short periods of time; as well as dwellings build by private owners and by small developers.
2. One of the two areas should include residential dwellings built before 1965 and the other should include structures built after 1999. The median construction years of the units in the neighborhood was obtained from 2010 census at the block group level.
3. The study areas should include both low-density developments with large parcels (larger than 20,000 square feet) and high density developments with small parcels (smaller than 8,712 square feet), based on the size of the residential parcel recorded in the 2011 Maricopa County Assessor parcel database.
4. The boundaries of the study area should be delineated by Traffic Analysis Zone (TAZ) boundaries from 2000. For this study the use of TAZ boundaries facilitate incorporation of transportation data that is typically recorded at the TAZ level.

Based on these above listed criteria, the resulting study areas included 8,543 single-family units located in the City of Phoenix and the Town of Gilbert. The study areas cover over 3,000 acres of urban area, with various mixes of commercial, vacant and agricultural land uses, and it is divided in ten TAZs of various sizes.

After delineating the two large areas, we further organized each in to two groups by high and low residential densities. Each study area group reflects a specific density, median construction year, street layout and development type. A summary of the main characteristics of the four distinct neighborhoods are provided in Table 1.

4. Data and methods

We conduct separate analysis for the two components of our neighborhoods we consider within our LCA system – the single-family residential inventory and roadway infrastructure inventory. The single-family inventory and analysis follows closely the data and results from the earlier study by Frijia et al. (2012). We use a similar parametric model to account for the variation in single-family units in our two neighborhoods. Rather than acquiring the specific building blueprints and deriving individual bill of material and labor estimates, the economic data associated with material quantities, and labor and equipment costs for a standard building design of average construction quality is estimated using a construction estimating software – CostWorks 2011, by RSMeans . A comprehensive database listing all the materials used and their cost for each one of the 8,543 existing units in the study area does not exist, nor would it be possible to account for all the modifications, remodels and upgrades done over the years.

Table 1: Descriptive information about the four selected neighborhoods

Characteristic	Unit	Group 1	Group 2	Group 3	Group 4
		Central city - High density	Central city - Low density	Suburban - High density	Suburban - Low density
Density	du/acre	8	5.3	9	0.7
Median construction year [b]	years	1940	1962	2004	1976
Population [d]	people	5657	2720	19616	1007
Total residential parcels [b]	count	2499	1576	7176	321
Total single family dwellings [b]	count	1871	509	5630	302
Total multi-family dwellings [b]	count	628	1067	1546	19
Total net residential area (parcel) [b]	acres	313	296	800	401
Total net residential floor space	sq. feet	2,246,790	1,590,726	11,481,632	730,750
Average dwelling size	sq. feet	899	1,009	1,600	2,537
Total commercial parcels [b]	count	373	87	414	61
Total net commercial area [b]	acres	147.32	60.75	450	92.5
Total net vacant area [b]	acres	7.34	22.42	498.3	22.4
Total agricultural area	acres	0	0	155.3	20.86
Principal arterial roads [c]	miles	4	5.02	10.5	4
Collector roads [c]	miles	2	1	1.5	0
Local roads [c]	miles	18.05	9.38	66.1	8.9

[b] 2010 Maricopa County Assessor; [c] U.S. TIGER; [d] This value was adjusted because one of the census blocks extends beyond the TAZ boundary.

The primary input parameters used in this software are: unit size, number of stories, construction quality, exterior wall finish, and roof material type. All the other material assemblies are automatically included. The source of these input parameters was the 2011 Maricopa County Assessor Residential Master file. To perform a parametric LCA analysis of the five unit sizes for all possible attribute combinations listed above, would require 720 model runs. However, some of the material listed are seldom used or no longer used in new construction (i.e., asbestos). Therefore, only the most recurrent combinations were used which, when combined, recurred in more than 90 percent of the units. Accordingly, five types of roof material (wood, asphalt shingle, built up concrete tile, and clay tile) and four types of exterior wall composition (frame wood, 8" painted block, 8"stucco, and brick) were considered. This reduces the number of required model runs to 200. For the remaining units, proxy values were used.

The PaLATE tool was used to estimate the energy and environmental impacts of 1-mile lane (both direction) of typical roadways. Rather than running the PaLATE tool for each roadway type in the study area, the original output of the PaLATE tool was adjusted to match the roadway geometries of the City of Phoenix and Town of Gilbert. This table provides total energy (GJ) and total GHG emission associated with construction and maintenance of one mile (units), curb to curb, of arterial, collector and local residential roads under normal use condition (Chester, 2008).

5. Study results

The results from our analysis are provided in Table 2. indicate that Suburban-high density (Area 3) is the most densely developed, and the most energy and GHG intensive area among the four case study areas included. The estimated single-family residential and road life cycle energy in this area is about 150 Gigajoules per year, which generates more than 2.6 Kilotons of CO2e yearly. On average, each dwelling accounts for 21 Gigajoules of energy and 1.3 tons of CO2e yearly. On per dwelling basis, the energy intensity of this area is only surpassed by its neighboring low-density residential area in Gilbert. One key contributor to the high-energy intensity of this area is the type of residential buildings located here. About 71 percent of all the units in this area are two-story and they are mostly stucco on a wood-frame with cement tile roofs, which is the one of the most energy intensive material combination for both one and two-story units.

The Suburban-low density area (Area 4), also in Gilbert, is the least dense and the least energy intensive of all the areas included when aggregate estimates are compared. However, when normalized for either population or the number of dwelling units, the results indicate that it is the most energy and GHG intensive. The residential units here account for over 53 Gigajoules of energy and 2 tons of GHG emissions per year on average. About 95 percent of the units in Suburban-low density are single story and half of them are made of cement blocks and asphalt shingle roofs. However, to understand better the differences, and meaning, of these LCA results, it is necessary to compare them in light of actual differences in the built environment previously listed in Table 1.

Table 2: Energy Intensity and GHG Emissions of Four Study Areas

Normalized by	Attribute	Unit	Central city High density	Central city low density	Suburban high density	Suburban low density
Adjusted Population	Residence C&M Energy/person	GJ/year-person	4.49	6.71	6.57	8.16
Adjusted Population	Road C&M Energy/person	GJ/year-person	1.94	3.30	1.07	7.07
Adjusted Population	Total C&M energy/person	GJ/year-person	6.44	10.01	7.64	15.24
Adjusted Population	Residence C&M CO2/person	ton/year-person	0.32	0.48	0.47	0.58
Adjusted Population	Road C&M CO2/person	ton/year-person	0.15	0.25	0.13	0.55
Adjusted Population	Total C&M CO2/person	ton/year-person	0.47	0.73	0.60	1.13
Dwelling units	Residence C&M Energy/dwelling	GJ/year-dwelling	10.08	11.32	17.94	28.46
Dwelling units	Road C&M Energy/dwelling	GJ/year-dwelling	4.4	5.6	2.9	24.7
Dwelling units	Total C&M energy/dwelling	GJ/year-dwelling	14.4	16.9	20.9	53.1
Dwelling units	Residence C&M CO2/dwelling	ton/year-dwelling	0.7	0.8	1.3	2.0
Dwelling units	Road C&M CO2/dwelling	ton/year-dwelling	0.34	0.43	0.35	1.90
Dwelling units	Total C&M CO2/dwelling	ton/year-dwelling	1.1	1.2	1.6	3.9

At the other end of the energy intensity scale, The Phoenix-high density area (Area 1) is the least energy intensive of our study areas when normalized by dwelling or population. As shown in Table 2, an average dwelling in this area accounts for 14.4 Gigajoules of energy per year for construction and maintenance of both the dwelling and its share of the road infrastructure. The energy intensity of dwellings in this area is only 27 percent of that in the most energy intensive area, which in this study is Suburban-low density (Area 4). The Central Phoenix area on a per dwelling basis is more energy efficient than its suburban counterpart regardless of density of dwelling units. However, when normalized by population (adjusted for vacancy), density of units becomes the driver for the estimates of energy intensity since it is lower for higher density areas than the low-density areas in either the city or the suburbs.

6. Conclusion

Our results clearly indicate that comparative measures of energy intensity are sensitive to the units of normalization applied. When energy and GHG emissions are measured on a per capita basis, high density areas, regardless of their location in the inner city or suburbs, turn out to be the most energy efficient neighborhoods. However, when normalized values per dwelling are used, suburban developments, irrespective of the density of developments tend to be more energy intensive. The difference in energy intensity between central city high and low density areas is marginal (less than 10%) when normalized values per dwelling are considered. The same difference grows to 36 percent if the values are normalized by population.

Our findings have clear implications for urban policies – specifically policies that provide guidance for planning urban neighborhoods. We find that the most pertinent area of regulations that would affect the energy profile of neighborhoods is subdivision regulations. The guidelines on layout of new subdivisions, their plot densities and the network of streets can be significant in reducing urban energy use. There are already guidelines and incentives in place for reducing building energy, such as through Leadership in Energy Efficient Design (LEED) certification. Recognizing the importance of neighborhood design, LEED for neighborhood development (LEED-ND) is now being vetted and pilot tested for implementation. Our research provides a methodology for measuring neighborhood energy demands and offers a quantitative basis for making policy decisions.

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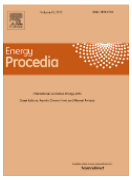

Biography

Subhro Guhathakurta is Professor of City and Regional Planning and Director of the Center for Geographic Information Systems at Georgia Tech. He is an author of 5 books and monographs and over 70 scientific papers. He has held visiting appointments at the Center for Urban Spatial Analysis at University College London, the Indian Institute of Information Technology, Bangalore, and at the Center for Sustainable Urban and Regional Futures at the University of Queensland in Brisbane. More recently, he held the German National Science Foundation (DFG) Mercator Guestprofessorship at Technische Universitat Kaiserslautern, Germany.