Title
The Energy Impact of Urban Form: An Approach to Morphologically Evaluating the Energy Performance of Neighborhoods

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The Energy Impact of Urban Form:
An Approach to Morphologically Evaluating the Energy Performance of Neighborhoods

By

Ye Kang Ko

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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of the

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Committee in charge:

Professor John D. Radke, Chair
Professor Louise A. Mozingo
Professor Edward Arens

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Abstract

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Doctor of Philosophy in Landscape Architecture and Environmental Planning

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This dissertation empirically evaluates the association between urban form and the energy performance of neighborhoods focusing on their energy demand and on-site green energy supply. Urban form, the spatial pattern and density of urban physical objects, such as: buildings, streets, vegetation and open space, have a considerable long-term influence on macro-scale environments. Besides their well-known impacts on vehicle trips, the effects of urban form on space-conditioning energy use and on-site energy generation has recently received attention most likely as a result of the energy crisis of the late 2000s.

However, these complex effects of urban form on their net energy savings, generation and potential trade-offs have not been rigorously and comprehensively evaluated due to computational limitations and the lack of data rich environments. In addition, we do not understand what kind of urban form is best for utilizing the benefits from new technologies (for example, efficient vehicles and solar photovoltaics) as they are rapidly being adopted in urban landscapes. Given the inertia of the built environment, it is imperative to alter urban form based on a thorough understanding and comprehensive assessment of urban systems. As our scholarship and practice of green initiatives has been somewhat piecemeal and short-sighted, it is critical that we construct comprehensive models to study the relationships between urban form and energy efficiency.

Given this challenge, this dissertation assesses the impact of urban form on energy use and on-site green energy generation by developing and applying an empirically based data rich model. This research also provides an approach for evaluating potential trade-offs between energy demand and supply given specific urban form. Given these goals, this dissertation focuses on answering three questions that each represent energy demand, supply and trade-offs that are affected by urban form:(1) does urban form have impact on residential space-conditioning energy use?; (2) does urban form have influence on on-site solar energy potential?; and (3) how does the trade-off between vehicle energy use and on-site solar energy potential vary over urban density?

To best account for a complex real-world environment in the model, this dissertation employs advanced three-dimensional urban models derived from Geographic Information Systems (GIS)and Light Detection and Ranging (LiDAR) data. This method successfully captures the physical conditions of real landscapes, including vegetation, which has been impossible to obtain until recent years. After extracting urban form and demographic variables through spatial analyses, it applies multivariate analysis to assess the impact of urban form on energy use and on-site energy generation controlling for other factors. The Cities of Sacramento and San Francisco, California are used in this research, however it is argued the approach is universal in nature.

This dissertation reveals that urban form matters in reducing cooling energy demand and increasing on-site solar energy supply in cities. The results show higher population density, east-west street orientation, higher green space density within a 100ft radius and a higher sum of tree heights on the east, south and west sides of houses have statistically significant effects on reducing summer cooling energy use after controlling for other variables. With regard to impacts of trees on on-site solar energy generation, this research also discovers higher tree density, higher average tree heights and a higher variance of tree heights have significant impacts on reduction in the average rooftop insolation. Examining the trade-off between on-site solar energy potential and vehicle energy use, the results show that the density threshold that allows personal vehicle energy use becomes smaller than rooftop solar potential, changes as vehicle and solar technologies improve and different combinations of them become available.

This dissertation is the first comprehensive validation of many of the early theoretical works on climate responsive urban design and on-site solar energy guidelines in the 1960s through the early 1980s. It supports the argument that more energy related incentives and regulations are imperative not only on a single building scale but also for its neighboring environment on a community wide scale. Finally, this research provides a new approach to how city planners can respond to technological advances and policy shifts in energy related areas.

To my parents, who taught me the value of vision, knowledge and love,

and

To my beloved husband Junhak, who shares the vision, knowledge and love with me.

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List of Acronyms

AB32	Assembly Bill 32
ACS	American Community Survey
BATS	Bay Area Travel Survey
CBD	Central Business District
CV	Coefficient of Variation
DEM	Digital Elevation Model
DSM	Digital Surface Model
GHG	Greenhouse Gas
GIS	Geographic Information System (Science)
HLM	Hierarchical Linear Modeling
HVAC	Heating, Ventilation and Air-Conditioning
ICC	Intra-class Correlation
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
O-D	Origin - Destination
OLS	Ordinary Least Square
PV	Photovoltaic
SB375	Senate Bill 375
SMUD	Sacramento Municipal Utility District
S/V	Surface area to Volume
TAZ	Traffic Analysis Zone
VIF	Variance Inflation Coefficient
VKT	Vehicle Kilometers Traveled
VMT	Vehicle Miles Traveled
ZNE	Zero-net Energy

Acknowledgement

My education up to my PhD has been a long journey towards understanding how human settlements can evolve in a more sustainable and responsible way, which respects the rights of all people and wildlife. With this dissertation, I have just taken the first step towards solving this gigantic problem. I believe this first step is an essential foundation for my new journey as a professor. This achievement would have been impossible without the support from my family, friends, colleagues and professors who I met at Berkeley.

Above all, I have the deepest appreciation for my advisor and the chair of the committee, Professor John Radke, who has consistently given me his full support. With great patience and trust, he has persistently encouraged me to ask imperative research questions and has given me excellent guidance towards finding a way to answer questions. I was truly inspired by his passion, devotion, insights, intellect, integrity and long-term vision as a scholar and a teacher. Beyond an academic advisor, he is my life-long friend, mentor and a role model. It is hard to find expressions that articulate my gratitude towards him. I am very grateful to have him in my life.

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I. Introduction

1.1 Background

Reducing the use of fossil fuel is a primary step to solving numerous economic, political and environmental problems on the planet. Rapid depletion of fossil fuel will have tremendous impacts on the global economy by paralyzing most contemporary human activities. Major scientists like the Intergovernmental Panel on Climate Change (IPCC) (2007) proved that that climate change is not a myth but a real challenge and anthropogenic greenhouse gas concentration as a result of using fossil fuels is the major contributor. We are witnessing escalating omens of climate change around the world, from natural disasters to rising sea levels and their resulting costs and damages, especially to urban areas. As a reaction to and for the mitigation of climate change, building sustainable cities through reducing oil use has been the hottest agenda of urban planning over the last decade.

Among various strategies, creating a sustainable urban form that reduces oil dependence has been a central matter in scholarship and practice. It is key to solving numerous urban problems such as; reducing oil use in cities would reduce the impacts on the environment and human health, foster economic gain and equity and create more resilient and peaceful cities (Newman et al. 2009). To create energy saving urban forms, planners suggest various solutions: compact development with transit access, construction of green buildings, increasing on-site renewable energy supplies and more. In recent years, landmark legislation in California and programs including California's Assembly Bill 32 (AB32), Senate Bill 375 (SB375) and Go Solar California have been implemented in order to support these "green" initiatives[1].

However, building a sustainable urban form is a complicated task, not a straightforward goal that can be simply achieved through a collection of green initiatives. It requires a more sophisticated understanding of urban form and the optimum adaptation of each green technology. The State of California is one of the leading states in promoting energy efficiency and has just begun with zero-net energy (ZNE) buildings that meet their energy needs with renewable energy that is generated on-site[2]. However, we have little understanding of how to achieve ZNE on broader city and regional scales. Current initiatives rarely account for potential trade-offs between different initiatives and have not measured what or how much they might be. New technologies – for example, efficient vehicles and solar photovoltaics– are rapidly being developed and we do not fully understand what kind of urban form would be best for utilizing the benefits from all these technologies. Moreover, because of the inertia of the built environment, altering urban

[1] In 2006, California passed California AB32 (the Global Warming Solutions Act) with the aim of reducing GHG emissions to 1990 levels by 2020. One of the major means to achieve this target is controlling urban density and land use. SB375, also known as the anti-sprawl bill, was passed on January 1, 2009 in order to discourage vehicle use by promoting compact and infill development with mixed-land use and transit access. Go Solar California, a statewide campaign, was initiated targeting to provide 3.3 billion dollars of incentives to promote on-site solar energy with 3,000 megawatts of solar energy systems for homes and businesses by the end of 2016.

[2] Torcellini et al. (2006) documented four definitions of "net zero energy" : *net-zero site energy, net-zero source energy, net-zero energy costs* and *net-zero energy emissions*. Currently these definitions of ZNE are mostly implemented at a building scale. In the United States, "zero net energy building" generally refers to net-zero site energy. In this type of building, the amount of energy produced by renewable energy sources available on site is equivalent to the amount of energy consumed by the building.

forms must be based on thorough and comprehensive assessment. In order to ensure the best practices, we must first assess the impacts of existing urban forms on energy performance of cities and suggest guidelines for minimizing building energy use, vehicle energy use and maximizing on-site green energy generation.

After the oil shock in the 1970s, planners and designers had developed climate responsive design guidelines for buildings, sites and neighborhoods. Many design and planning principles that incorporate passive and active solar systems have been studied in the 1970s and the early 1980s. At that time, small scale experiments or simple simulation studies were dominant for testing the effectiveness of these principles because an assessment of real world landscapes using empirical data was virtually impossible. Unfortunately, these vigorous efforts did not last long as oil prices dropped. Many energy efficient design and planning guidelines became “theories” and have rarely been practiced in the real world for the past three decades. The recent energy and economic crisis in the late 2000s awakened our attention to this subject but our understanding of energy efficient urban forms has not made progress since 1970s.

This dissertation explores an approach for evaluating the sustainability of urban forms using energy as an indicator. Urban form, the spatial pattern and density of urban physical objects, such as: buildings, streets, vegetation and open space, has a considerable impact due to its long-term influence on macro-scale environments. When most energy efficient design principles were developed in 1970s, the effects of different urban forms on energy saving and generation had not been rigorously evaluated due to computational limitations and lack of data rich environments. Until now, academia has not helped to provide reliable quantified information to develop effective climate change policies as the lack of rigorous methodologies used to model complex urban environments was missing.

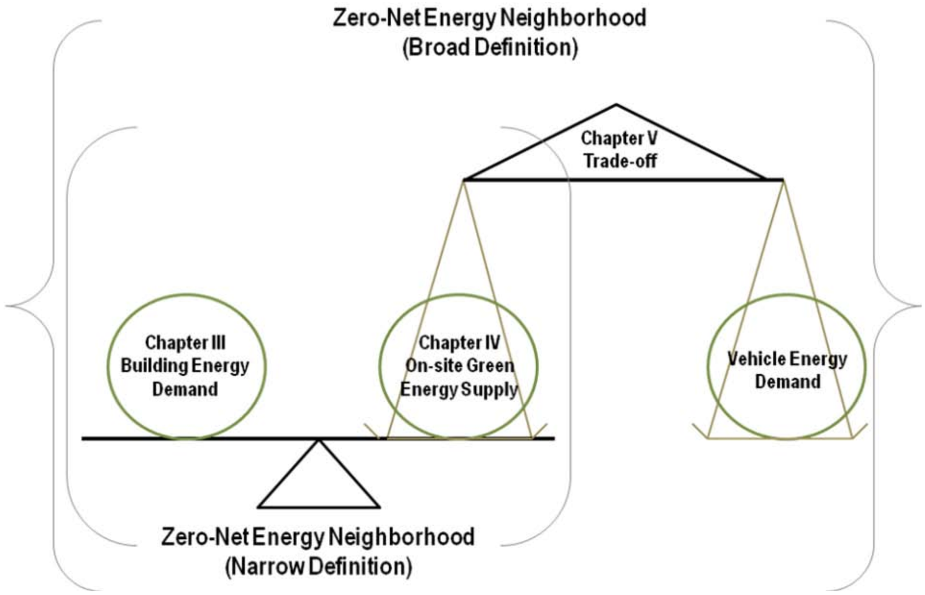
Given this challenge, this research investigates the relationship between urban form and the energy performance of communities by using an empirically based data rich model. It assesses the impacts of urban forms on energy use and on-site green energy generation. It also provides an approach for evaluating potential trade-offs between different green policies. Given these goals, this dissertation will focus on three themes: 1) the impact of urban form on residential energy use (Chapter III); particularly space-cooling demand, 2) the impact of urban form on on-site solar energy potential (Chapter IV), and 3) the trade-off between vehicle energy use and on-site solar energy potential over urban density (Chapter V).

To best model the complex real-world environment, this study employs advanced three-dimensional urban GIS models derived from Light Detection and Ranging (LiDAR) data. This method successfully captures the physical conditions of real landscapes, including vegetation, which has been impossible until the present time. After extracting urban form and demographic variables through spatial analyses, multivariate analysis is used to assess the impact of urban forms on energy use and on-site energy generations controlling for other factors. The Cities of Sacramento and San Francisco, CA are used for this study, but this approach is applicable for any area.

The contribution of this dissertation would be as follows:

- This dissertation reveals the impacts of urban form on energy use and on-site energy generation in cities through an empirically based data rich model. Planners can understand how energy demand (both stationary and mobile) and on-site renewable energy supplies interact with the built environment under the notion of "ZNE cities" (Figure 1.1).
- The findings of this dissertation provide important implications for the research and the practice of building energy efficient neighborhoods. For example, the findings of Chapter III inform planners as they quantify the impact of existing physical designs of neighborhood-scale energy performance. They urge that more energy related incentives and regulations are imperative not only on a single building scale but also for its neighboring environment on a community scale.
- This research recommends the development of new guidelines for municipal climate action plans as they attempt to solve two conflicting goals. The findings of Chapter IV spatially assess the location of houses that show potential conflicts between trees and rooftop solar energy generation. The results of Chapter V urge the rethinking of the desirable density that maximizes on-site solar energy generation and minimizes vehicle energy use— in order to reduce net-energy use and associated net GHG emissions.
- This research provides a new approach to how city planners can respond to technological development and policy shifts in energy fields. For example, Chapter V guides planners in defining a density threshold that maximizes net energy and suggests how to set density standards for sustainable development as energy-efficient electric vehicles and on-site solar generation become more efficient and popular.
- The research provides a successful example of the application of advanced spatial modeling using three dimensional data to answer complex urban problems. Using this method, planners can further develop urban form metrics that classify the neighborhoods along a spectrum of energy performance.

Figure 1.1 Evaluating ZNE neighborhoods



1.2 Organization of the Study

This dissertation contains six chapters:

Chapter I provides the background of the study, problem statement and research design of the dissertation.

Chapter II serves as the literature review for this dissertation by discussing urban form attributes that affect residential space-conditioning energy use and on-site solar PV potential. It reviews the climate responsive urban design principles and research finding in relation to each urban form attribute that affects building energy use and on-site solar energy generation. It also points out the gap in literature and address research needs.

Chapter III explores the demand side of ZNE cities by assessing the impact of urban form on residential space-cooling energy use. Many climate responsive urban design theories discussed in the previous chapter show various design and planning guidelines for saving space-conditioning energy use but the actual effects of such techniques are controversial and are rarely quantified using empirical data. Given this gap in literature, this study quantifies the effects of urban form variables on residential cooling energy use using empirical electricity billing data. It includes urban form variables extracted from GIS and LiDAR data. Using multivariate analysis, it examines how urban form and structures of property and socio-demographic variables affect residential cooling and heating energy use. As a result of the site selection process that considers data accessibility and the variation in temperature during the year, the southwest section of the City of Sacramento is chosen for this study.

Chapter IV moves onto the supply of on-site green energy in cities, after investigating the demand side of ZNE cities. It investigates the impact of urban form on on-site green energy potential, particularly focusing on the effects of trees on residential rooftop solar energy. Among urban form variables, the impact of trees on rooftop solar potential is very complicated because of their trade-off between energy savings and energy generation. Urban trees provide various benefits including mitigating urban heat island effect and saving energy. However, their potential counter impact on another green technology (here, the rooftop solar energy generation) has rarely been investigated. Given this interesting conflict, this study measures the impact of trees on rooftop solar energy potential and demonstrates the spatial pattern of a certain level of impact across the city landscape. The City of San Francisco is selected as the study site because San Francisco contains a rich set of typologies of buildings and trees, thus best meeting the needs for constructing a data rich model to answer the research question.

Chapter V incorporates vehicle energy use in the definition of ZNE neighborhoods and addresses the trade-off between on-site solar energy potential and vehicle energy use across population density in the City of San Francisco. Compact development reduces vehicle energy use, however, it generates more shade from neighboring buildings and results in less available rooftop area per person. Using travel survey and 3D GIS data derived from LiDAR, this study estimates Vehicle Kilometers Traveled (VKT) and assesses available rooftop areas per person for each Traffic Analysis Zone (TAZ) in the City of San Francisco. Vehicle energy use and rooftop solar potential across population density are computed with 16 scenarios of technological advances in the efficiency of solar devices and vehicles. This chapter is the bridge of this research that moves towards future studies, which aim to optimize our urban forms using the best ways to adopt new green technologies.

Chapter VI summarizes the results of each chapter, and provides the contribution and policy implication of this dissertation. Finally, it addresses the limitation of the research and suggests the directions for future research.

II. Literature Review

In this chapter, I provide a literature review of two main themes of this dissertation: the associations between: (1) urban form and space-conditioning energy use and (2) urban form and on-site solar energy potential. This chapter discusses basic principles of climate responsive and solar energy planning and design, reviews the research findings from previous studies and addresses the gaps and research needs.

2.1 Urban Form and Space-conditioning Energy Use

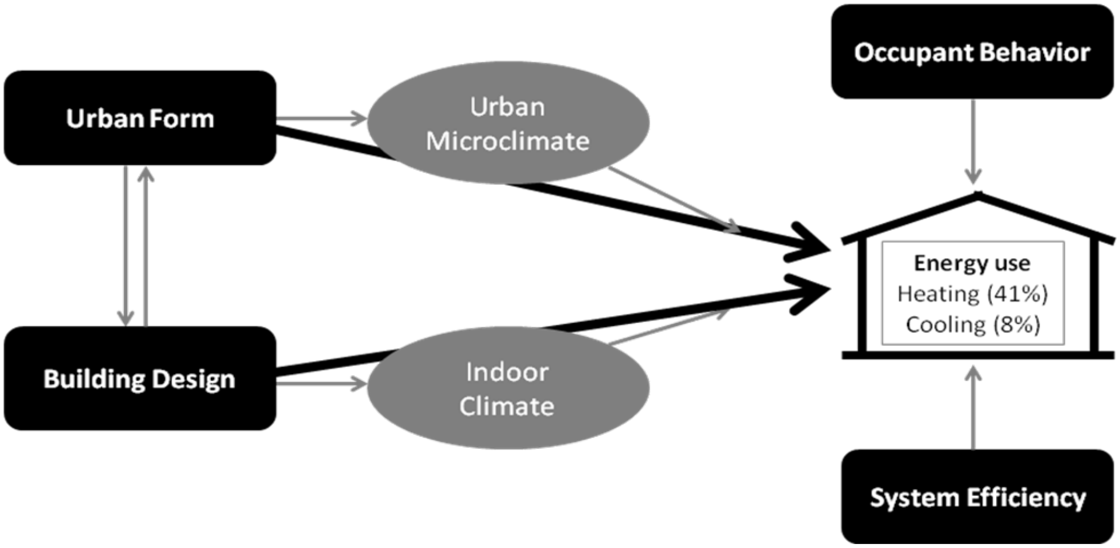
2.1.1 Introduction

Does urban form affect residential energy use? The answer to this simple question is controversial. Many planners would agree that urban form affects transportation energy use based on extensive research findings; however, there are few studies that have investigated whether urban form has a significant impact on the energy performance of buildings. How would architects respond? Building energy use can be explained as a function of urban form, building design, energy system efficiency and occupant behavior (Figure 2.1) (Ratti et al. 2005). Among these variables, determining the effect of urban form on energy use has been elusive (Lantsberg 2005; Mitchell 2005; Ratti et al. 2005).

Building energy consumption exceeds industrial and transportation figures in developed countries such as the U.S. and the E.U. (Pérez- Lombard et al. 2008). In the U.S., buildings are the largest source of energy consumption and account for 41% of the total energy consumed. Residential and commercial sectors respectively consume 22% and 19% of the total energy use (Energy Information Administration 2008). The building sector's contribution to energy use is even greater in places like London where people use more public transportation (e.g. for London the ratio of energy used in buildings versus transportation systems is around 2.2:1) (Mitchell 2005; Steemers 2003). Given this fact there is little doubt that more aggressive efforts need to be made towards improving building energy performance by promoting a better understanding of energy consumption.

Non-spatial options for reducing building energy use such as: improving HVAC (Heating, Ventilation and Air-Conditioning) systems, changing people's behavior and pricing fuels, all undoubtedly have a significant impact. However, even if the impact of urban form on building energy use is smaller than those of other contributors, it can still be considerable due to its long-term impact on numerous buildings in a macro-scale environment.

Figure 2.1 Four main factors that affect building energy use



Building energy use can be explained as a function of urban form, building design, energy system efficiency and occupant behavior (Ratti et al. 2005). Urban forms affect urban microclimate, which influences space-heating and cooling energy demand.

Since the energy crisis in the 1970s, many researchers, mostly in architecture fields, extended their attentions from building design itself to the impact of urban design on urban climate and building energy use. Many climate-response and passive solar neighborhood designs and landscape planting guidelines were extensively studied from the late 1970s into the early 1980s. Simulation studies have been conducted focusing on the effect of one or two of these variables (e.g. house size, type, street layout, and trees) on microclimate (e.g. solar access, wind flow, and air and surface temperature), thermal comfort, and building energy use. These subjects were mostly dominated over several decades by architecture and related design fields.

As the needs for urban and regional policies that focus on greenhouse gas (GHG) reduction increases, researchers in planning began to discuss whether or not there is a considerable impact of planning variables (mostly in relation to urban density) on building energy use. Using government statistics like the U.S. Residential Energy Consumption Survey (RECS), a few statistical studies have been conducted in energy policies and planning. In 2008 Ewing and Rong's recent study became a milestone that prompted planners to begin to look at how urban form variables such as: housing size, housing type and density affects heating and cooling energy consumption using multivariate statistical analysis (Ewing and Rong 2008). It had received a lot of attention and at the same time, it immediately received skeptical comments by Randolph (2008) and Staley (2008). The major criticisms were: (1) doubt about the legitimate link between the complex dataset and methods used and the conclusions, (2) the ignorance of the bigger impacts from other means – energy pricing and developing efficiency technologies and (3) doubting whether complex statistical analysis was necessary instead of simply using an engineering simulation model that could have easily controlled other variables.

Although both architectural and planning approaches have been contributing to the energy conservation of different building and neighborhood forms within each field, literature has been divided and there has been a lack of communication between the different fields. Architectural studies have been focusing on developing design guidelines for passive solar homes and landscape planning but the impact of energy conserving layouts and community design have rarely been quantified and considered in practice; except in a few exemplary communities like the Village Home in Davis, California in the 70's or during the recent energy crisis. On the other hand, planners have been investigating the macro-scale relationship between urban form variables and residential energy use but are rarely aware of the variation of architectural designs that are associated with planning variables.

This review aims to create a common ground for literature reviews on planning and design that aim towards the energy conserving urban form. Urban form variables, in this study, are described as planning and design characteristics across the scale of built forms that have been discussed in the design and planning literature. They affect building energy consumption as follows: house type, density (compactness and population/dwelling unit density), community layout (street orientation and building configuration), vegetation planting and surface coverage. Although planning and design naturally focus on different variables of interests and methods, there must be an effort to present the findings of previous literature in both fields because those variables are correlated spatially and all together contribute to energy conservation.

This literature review aims to provide guidance for researchers who want to investigate the impact of various urban form variables on building energy use. This review starts by browsing through a spectrum of design principles and links them with research findings. It also aims to update the bibliography of climate responsive housing design, layout, planning and to point out gaps in the literature by addressing what has been found and what was missing.

In building energy use, the focus is on the residential structures alone, which is done in order to avoid the variation of energy operation and occupant behavior due to different types of activity. The previous literature that is reviewed in this review, discusses a direct relationship between urban form variables and residential energy use, especially space-conditioning, focusing on the effects of house type, density, community layout, vegetation planting and surface coverage. In order to focus on the purpose of this review, a number of studies that investigate the effect of urban design on microclimate (but do not touch on energy use) were excluded from the review but were partially mentioned in order to explain the full path of these associations. Studies that evaluate the effectiveness of energy-conserving architectural designs, building retrofits and occupant responses (e.g. the well-known Princeton's experiments at Twin Rivers- Socolow 1978ab) are not within the scope of this review. The geographic scope is the U.S., Canada, and the U.K.

The literature covered includes: (1) climate responsive housing form and layout principles, (2) simulation modeling research and (3) statistical studies with empirical data. Peer-reviewed journal articles are mainly included in this review. Non-peer-reviewed studies that are cited in peer-reviewed articles are also referred to in this study.

2.1.1 Climate Responsive Urban Design Principles

Planning and design factors across the scale contribute to residential energy consumption in that it determines microclimates such as daylight, solar radiation (heat gain), wind flow (wind shelter or ventilation) and local temperature (urban heat island) (Figure 2.2). A number of studies describe the principles of climate responsive housing form, street layout, building configuration, housing density and landscape planting in relation to their function in solar access and control, natural ventilation, and microclimate (Table 2.1). Since climate is a dominant factor of space-conditioning energy consumption, specific guidelines are made for different climate zones (four climate categories: hot-dry, hot-humid, cold-dry, cold-humid) (Table 2.2).

Figure 2.2 Flow chart of how urban form variables impact urban microclimate and residential space-conditioning energy use

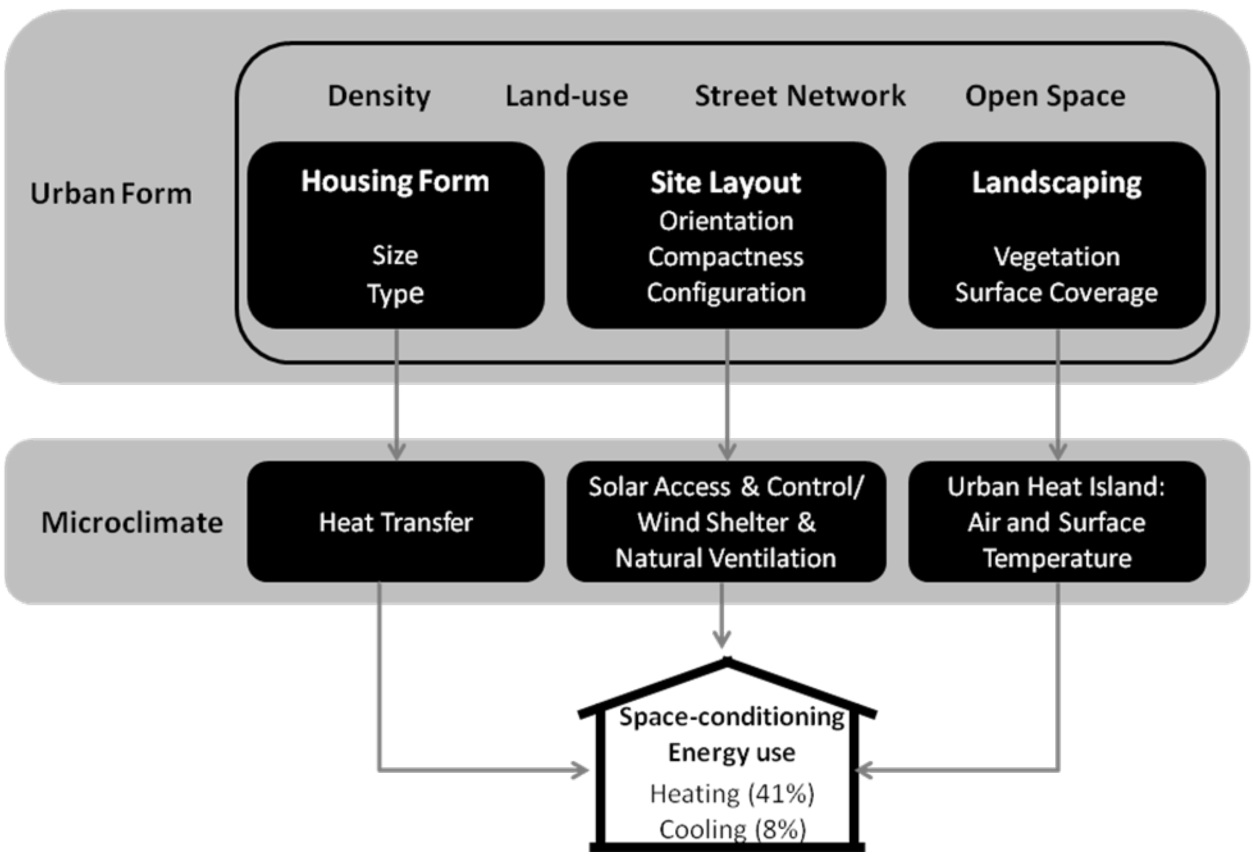


Table 2.1 Chronological review of selected classic studies of energy conserving site layout, community design, and landscape planning

Author	Year	Focus	Note/Contribution
Olgyay	1963	Principles of bioclimatic approach to building design and site planning.	Seminal academic study in architectural regionalism.
McClenon & Robinette (American Society of Landscape Architects Foundation)	1977	Comprehensive instructions for energy conserving site selection and planning focusing on landscape planting.	Emphasis on natural factors (e.g. land form) in energy conserving site planning with case studies, Good bibliography by topics.
Center for Landscape Architectural Education and Research	1978	Hieratical guidelines for energy conserving site selection, design, and planning.	Great hierarchy of site planning and design guidelines—(Gross & discrete site selection, plan layout, and building relationship) for four climate regions; excellent annotated bibliography.
A.I.A. Research Corporation	1978	Regional guidelines for passive energy conserving building design.	Consultant report to US HUD and DOE; Detailed climate analysis and design guidelines for 13 climatic regions of the U.S.
Erley & Jaffe (American Planning Association)	1979	Site planning guidebook focusing on solar access.	One of a three part series of consultant reports regarding solar access to US HUD and DOE.
Knowles	1981	Architectural and urban design applications using "solar envelop".	Seminal study that introduces the concept of solar envelops; extended work from Knowles and Berry (1980).
Hammond et al. (Living Systems)	1981	Comprehensive manual for planning energy conserving residential development in California.	Consultant report to California Energy Commission; Specific manuals for six climatic regions of California; Excellent annotated bibliography.
Robinette	1983	Energy efficient site design for four climate regions.	Updated the work by Center for Landscape Architectural Education and Research (1978).
McPherson et al. (Landscape Architecture Foundation)	1984	Energy conserving neighborhood design (even including water conserving and embedded energy).	Beyond manuals, more comprehensive approach in energy conserving neighborhood design and landscape planning and providing alternative future community design case studies.
Brown	1985	Bioclimatic architectural design strategies.	The classic book on bioclimatic architectural design strategies; more detailed research focusing on buildings (in and outdoor) compared to Olgyay (1963).
Owens	1986	The association between building energy performance and urban form within a larger framework of energy efficient spatial structure.	Seminal book on energy integrated urban and regional planning.
Akbari et al. (Lawrence Berkeley Laboratory and US EPA)	1992	Guidebook on tree planting and light-colored surfacing for energy conservation and mitigate urban heat island effects.	Science-based guidebook incorporating associated environmental issues in implementing tree planting (e.g. water use, tree wastes, and smog).

Givoni	1998	Research in climatic building and urban design and guidelines for four climate regions.	Seminal book on climatic building and urban design; lots of research examples on human comfort and the effects of urban form on climatology.
Littlefair et al. (BRE)	2000	Site layout design and planning utilizing solar access, microclimate and passive cooling in urban areas.	Seminal book on climatic site layout planning; lots of examples from research.
Krishan et al.	2001	Design handbook for climatic building design.	Mostly building oriented but great illustration on process of climatic design from macro to micro-scale.

*This list includes selected studies that specifically focus on energy conserving site planning and design. A number of seminal studies on energy efficient building design or general site planning are excluded from this list.

Table 2.2General principles of climate responsive design by four different climate regions

	Hot and Dry	Hot and Humid	Cold and dry	Cold and Humid
Reference Region and City	Southwest (Phoenix, AZ)	Southeast (New Orleans, LA)	Great Basin (Ely, NV)	Northeast (Hartford, CT)
Climate Description				
Comfort level (% of the year)	Too hot for comfort: 37% Too cool for comfort: 48% Comfortable 15%	Too hot for comfort: 52% Too cool for comfort: 36% Comfortable 12%	Too hot for comfort: 0% Too cool for comfort: 92% Comfortable 8%	Too hot for comfort: 13% Too cool for comfort: 75% Comfortable 12%
Major climate challenges	Excessive dryness with high day temperature	Excessive heat and humidity	Strong cold wind	Extreme cold in winter, windy, high precipitation
Housing form and Community Layouts				
Major Design Strategies	Solar control	Natural ventilation	Wind protection	Wind protection
Site	South to Southeast slopes, flat lands, shallow north slopes	South, north, or any direction gentle slopes flat land	Lower sheltered and gently south to southeast slopes	Sheltered sides on gently south facing slopes
Housing Types	Compact 'patio' house type, townhouse or apartments	Individual high buildings	Townhouse or apartments	Townhouse or apartments
Compactness	Compact form	Dispersed form with open ends	Compact and clustered form	Mix of open and enclosed form
Street Orientation	East-West with 25° variation to southwest	East-West with 25° variation to southwest	East-West	East-West with 10° variation to northwest and 25° variation to southwest
General layouts	Narrow winding roads Uneven building heights Small, dispersed, and protected open spaces	Wide streets and open space Uneven building heights	Narrow winding roads Even building heights Small, dispersed, and protected open spaces	Mix of open and protected open spaces Even building heights
Vegetation	Deciduous trees in the south Trees in the east and west of the buildings Shaded and vegetated surface	Extensive shadow with mature deciduous trees to the north of buildings Some lightly twigged deciduous trees to the south of the buildings Shaded and vegetated surface	North of the buildings Short or deciduous trees acceptable to the south of the buildings	Deciduous trees in the south Evergreens to the north Low shrubs and hedges to divert wind

The contents are organized based on the AIA Research Corporation (1978), Erley and Jaffe (1979) and Golany (1996).

2.1.3 Urban Form Variables that Minimize Space-conditioning Energy Use

Housing Type

Housing type affects the building surface area to volume ratio (S/V ratio), which is most relevant to heat transfer. Given the same building volume, a single-family detached unit has a higher S/V ratio and is more likely to lose or gain heat, thus consuming more energy than a multi-family unit. While multi-family units share walls, a single-family detached homes requires all surface area to be exposed to the outside, thus being susceptible to outdoor temperature.

In general, housing type is correlated with housing size and density (Ewing and Rong 2008; Kaza 2010). Single family homes in suburbs generally are larger than urban multi-family houses. In theory, larger houses require more energy for space conditioning. Assuming that the height of each level is fixed, houses with larger floor areas have greater volumes of space that need to be heated or cooled. Whether or not housing types associated with neighborhood density affect residential energy consumption is one of the controversial topics in energy planning.

According to the Energy Information Administration (2008), single family housing uses more energy than multifamily housing per area, per household, and per person in the U.S. (Table 2.3). It appears that an average single family home uses less energy than a multi-family home per square foot. However, a single family home requires more energy use than a multi-family one because single-family homes are usually larger than multi-family homes. A household living in a single-family home consumes 1.7 times the energy than a household living in multifamily housing. A household member in a single family home still consumes 1.3 times more than a person in a multi-family unit.

If more details are seen, the difference of energy use between a single-attached house and a multi-family home with two to four units is almost unnoticeable. This fact indicates that when a single-detached house is compared with a multi-family house with five or more units, the difference is even bigger: the ratio is 1: 0.5 (per household) and 1: 0.67 (per person). Although the trend in the U.S. residential energy consumption shows that the energy consumption of all housing types decrease since 1978 (when the building codes were adopted), the gap between a single-detached house and a multi-family house with five or more units appears to be almost constant (Kaza 2010). Possible causes can be that the decreased gap due to new building codes was canceled out by the increase in house size of the single-detached homes. Unfortunately, because the majority of people in the U.S. live in single-detached homes, single-detached residents contribute to 74% of the total energy consumption; whereas multi-family homes with five or more units use only less than 5% in 2005.

Table 2.3 Residential delivered energy consumption intensities, by housing type

Type	*Per Square Foot (thousand Btu)*	*Per Household (million Btu)*	*Per Household Members (million Btu)*	*Percent of Total Consumption*
Single-Family:	55.4	106.6	39.4	80.5%
Detached	55.0	108.4	39.8	73.9%
Attached	60.5	89.3	36.1	6.6%
Multi-Family:	78.3	64.1	29.7	14.9%
2 to 4 units	94.3	85.0	35.2	6.3%
5 or more units	69.8	54.4	26.7	8.6%
Mobile Homes	74.6	70.4	28.5	4.6%
				100%

Source: EIA, A Look at Residential Energy Consumption in 2005, October 2008

[SIMULATION MODELING]
Building simulation tools that can test the variation of housing size, type, and other building characteristics have constantly evolved based on the scientific hypothesis. The classic study from the British Building Research Establishment (BRE) pointed out that a detached house could have space heating requirements three times greater than that of an intermediate flat of an equivalent size. This difference is of similar magnitude to that of poorly insulated units and to those with medium insulation standards (BRE 1975). Currently, many simple and complex building energy simulation models such as ResFen, Energy10, Ecotect, eQUEST, Energy Plus and DOE-2, are available to demonstrate such comparisons. The major advantage of simulation is that researchers can easily control the complex environment of climate, form, construction, HVAC, occupancy and energy price. They are then able to obtain the adjusted results. Also, the estimation from the model algorithms such as, DOE-2 and ASHRAE, have been validated with measured values (Diamond, Cappiello, and Hunn 1986; Meldem and Winkelmann 1998).

[STATISTICAL ANALYSIS]
In comparison to simulation, it has been more challenging to show the independent effect of different housing types on energy use when using an empirical approach. The challenge with adjusting other variables that explain residential energy use has been recognized as an inevitable limitation in this multivariate statistical approach (Owens 1986). Since the late 1970s, the RECS (the best and only existing large-scale energy consumption dataset for empirical studies in the U.S.) has been providing nationwide cross-sectional data as physical characteristics of the housing unit, the demographic attributes of a household, heating and cooling equipment, and fuel types. Such datasets have facilitated empirical studies to control various factors for certain levels, however, it still does not provide sufficient information for adjusting a huge variation in energy use data (Hirst et al. 1982; Kaza 2010; Randolph 2008). Variables such as: house age, income, and ownership merely provide indirect and limited clues for counting building design, efficiency of HVAC systems, and occupant behavior.

Most empirical studies generally agree that single family houses require more energy consumption compared to multifamily unit. Analyzing the 1978 National Interim Energy Consumption Survey with Ordinary Least Squares (OLS) regression, Hirst et al. (1982) argues that floor area is one of the key determinants of space heating and total residential energy use but there is a huge variation in energy use per unit of floor area. Using multiple regression with their own survey data, Holden and Norland (2005) argues that although there is a statistically significant difference in energy use among different housing types in Oslo, Norway, the difference in energy use between single-family and multifamily homes is reduced in housing built after 1980, due to the adaptation of new building codes. As the statistical methods evolve, Ewing and Rong (2008) use hierarchical model to take into account the shared characteristics of households in the same place. Using RECS, they argue that a household occupying a multi-family home consumes 54 percent less heating energy and 26 percent less cooling energy than those living in single-family detached homes. Kaza (2010) uses quintile regression as a method to overcome the high variability in the energy use dataset. Moving a household from a single family detached house to a multifamily apartment would reduce the heated area by more than $100m^2$, except for the 10^{th} and 90^{th} percentile, while the cooling energy savings is equivalent to reducing $40–70m^2$ of the cooled area (Kaza 2010).

In spite of the use of advanced statistical methods, it can be misleading to state the magnitude of absolute reduction unless using a perfect dataset with numerous relevant variables (Randolph 2008). A question with regards to the necessity of complex statistical methods to prove something that can be found with simple simulations still remains. However, empirical research is valuable when observing the pattern of energy use associated with the change of building options in the real-world environment, to indicate the relative significance of each variable on energy use, to evaluate the effectiveness of energy policies that have been implemented and to validate the results from simulation research. Its effectiveness will grow as richer datasets become more available.

Summary and Recommendations

The summary of findings and future recommendations are:

- The impact of housing type on space-conditioning energy consumption used to be more significant in the past, however, the difference among different types appears to be reduced by the adaptation of energy-efficient insulation and energy systems when controlling for size.
- According to government statistics and empirical research, housing type is strongly correlated with housing size and neighborhood density. Single family houses in suburbs are generally larger than urban multi-family homes and require more heating and cooling energy use.
- Although implementing building codes would help reduce energy use, blind faith in efficient technology would not be enough to achieve the goal towards an aggressive reduction of GHG emissions. Increasing multifamily housing and attached houses, reducing the unit size of single-detached houses, and adapting efficient technologies must be implemented simultaneously.
- Simulation research on the effect of housing type is widely available using various kinds of building energy simulation software. Compared to simulation research, empirical studies have hardly been conducted because of the limited accessibility of rich datasets. More empirical findings with a larger scale analysis will complement the current gap in the literature.

Density

Density can be described in two different ways: *compactness* from the architectural viewpoint and *population* or *dwelling unit density* from the planning perspective. Compactness is about how "tightly" buildings stand on the site. In a compact urban environment with high lot coverage and building heights, street width or aspect ratio (building height to street width—H/W) can be the key variable that affects residential energy use by influencing the potential for a building's solar access and natural ventilation.

Existing studies have investigated the impact of aspect ratio on microclimates such as solar access, wind flow, and outdoor comfort. For example, wide street design or low aspect ratio provides more space for allowing solar access and increases air temperature (Givoni 1998; Sharlin and Hoffman 1984) especially with the winter sun (Ali-Toudert and Mayer 2006; Arnfield 1990). Wide streets also promote freer air movement, thus facilitating natural ventilation in hot climates; however, they may have a negative impact on cooling due to the excessive solar exposure. Free air flow along wide streets can also aggravate the dust problem in hot and dry regions (Golany 1996). When narrow streets (high building height to street width ratio) are parallel to the wind direction, a straight wind tunnel (street canyon) increases wind speed. High wind speed exposes buildings to the same air pressure on both sides, thus reducing the natural ventilation of the buildings (Givoni 1998). The staggered and uneven height of buildings combined with narrow winding streets oriented toward the direction of the wind can divert strong wind to the streets and can promote the best natural ventilation (Aggarwal 2006) while controlling solar access (Hough 1995; Minne 1988). Due to the complex effects of aspect ratio on space-conditioning demand, the relationship has not been quantified through either simulation or by empirical approach.

As seen, the impact of compact urban form on residential energy use has a trade-off. A compact form is likely to block solar access, reduce heat transfer and provide shade, thus preferred in hot and dry regions. However such an arrangement can contribute to increasing heating demand by blocking solar access (Steemers 2003) and promoting UHI effects in modern cities where buildings themselves generate excessive heat and also minimizes heat loss (Krishan et al. 2001). Compact form has a negative effect not only on the passive solar conditioning but also on the opportunity for on-site solar energy generation. This occurs when solar access is blocked on rooftops if the buildings' vertical and horizontal layout is not carefully considered (Cheng et al. 2006; Hui 2001; Steemers 2003). In order to ensure solar access in a dense environment, research on solar envelop has been conducted for energy efficient urban design (Knowles 2003; Knowles and Berry 1980; Morello and Ratti 2009).

[SIMULATION MODELING]

The impact of compact urban form in general has been investigated through only a few simulation studies due to the requirement of complex computation. Steemers (2003) argues that the solar potential for housing in dense environments is reduced mainly due to obstructions from neighboring buildings. Using the LT model (Baker and Steemers 2000), Steemers reports that an obstruction of 30° to the south façade of a passive solar house can lead to a 22% increase of space heating energy when compared to an unobstructed façade. However, careful urban design that implements solar envelops can improve the issues of solar access from neighboring obstructions while accommodating for high density (Morello and Ratti 2009). Also, as for total heating energy savings, constraints on solar access in compact form can be compensated by heat loss reduction of compact form (Steemers 2003). Using the LT method for existing cities (London, Toulouse, and Berlin), Ratti et al. (2005) argues that the variation of energy use in different urban density and geometry was about 10%, which is still respectable. Central London, which represents higher compactness, requires less energy use than central Berlin that shows less compactness. However, continued studies on various urban forms are likely to provide a wider range of potential energy savings.

[STATISTICAL ANALYSIS]

The impact of density (household or population) on residential energy use began to receive a lot of attention in the last decade and has been investigated mostly through empirical approaches in planning. In planning density has received enormous attention as one of key variables that affect travel energy use since Newman and Kenworthy (1989) showed their well-known study on the association between urban density and travel energy use. About a decade later, since Lariviere and Lafrance′s study (1999) of Canadian cities was released; density started being recognized as a potential determinant of residential energy use. According to previous findings the impact of density on transportation energy use is much greater than its impact on residential energy use (Holden and Norland 2005; Kahn 2000; Lariviere and Lafrance 1999; Norman et al. 2006).

The effect of density on residential energy use is still very controversial. Lariviere and Lafrance (1999) report that higher-density cities use less electricity per capita than low-density cities but there is not a big difference. They predict that if cities of 1000 inhabitants per km^2 could increase their population density up to three times, the electricity use per capita would only be reduced by 7%. However, the effect of population density could have been greater if they had included residential gas consumption, which may have increased exponentially when used for heating during the very cold Canadian winter. Holden and Norland (2005) also argue that residents in dense areas use less energy than those in less dense areas in Oslo, Norway. However, their results are not as convincing because they may stem from a strong correlation between housing type and density that may have existed, but was not mentioned in their OLS regression. Using the 1993 RECS data of the U.S., Kahn (2000) finds that there is no significant difference in residential energy use between suburban areas and central cities. Using the quantile approach with updated RECS data, Kaza (2010) leads to the similar conclusion by reporting that neighborhood density itself (reflected in the urban rural classification, self reported) appears not to reduce energy use. Only apartments in large blocks are substantially different in their energy consumption profiles than single-family detached homes. However, Kahn (2000) and Kaza (2010)′s findings shows limitation in that they only took a simple dichotomy (city/suburb) into account instead of considering density as a continuum.

Rather than impacting energy use directly, recent research findings support that density indirectly affects residential energy use through other intermediate variables such as: housing type, size, urban heat island effect, ownership and income (Ewing and Rong 2008; Kaza 2010). Ewing and Rong (2008) note that the choice of housing type is strongly related to urban form; the odds that a household will live in multifamily housing are seven times greater for compact cities than for sprawling counties. Using path analysis, Ewing and Rong conclude that residents in sprawling counties tend to live in large, single-family detached homes and both lead to higher residential energy use. An average residential unit in a compact county would be expected to consume 20 percent less British Thermal Units (BTUs) of primary energy annually than one in a sprawling county. This is due to house type and size as well as 1 percent less annually due to urban heat island effect. The percentage reduction appears to be consistent with the simple engineering calculation conducted by Randolph (2008).

Summary and Recommendations

The summary of findings and future recommendations are:

- The impact of compact urban form affects microclimate in various and mixed ways: solar access, natural ventilation, heat transfer, and urban heat island effect. Given this mixed effect, more various options of compactness need to be evaluated either through simulation or empirical research in order to find the urban design strategies that increase net-benefits within each climate.
- The impact of density on energy use is also controversial. More rigorous research should be conducted while counting the limitation of energy datasets with careful research designs and richer datasets. Developing more comprehensive notions of urban density that incorporates both compactness and population density will aid in developing realistic variables that are close to real-world environments.
- Density has complicated associations with other green initiatives as well such as reducing travel demand and increasing on-site solar generation. Comprehensive evaluations on an optimum density that increases net-benefit must be conducted in planning and design. For example, refined strategies for increasing density and compactness to certain levels, while ensuring solar access through solar envelops must be implemented.

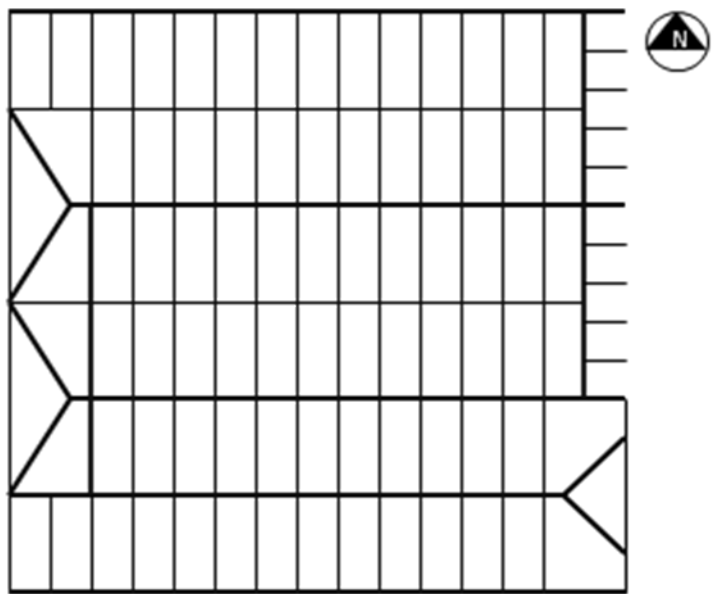
Community Layout

Site layout is one of the most critical design dimensions that determine adequate spacing and orientation in order to secure solar access for groups of buildings in communities. A building's orientation within 10° to 30° of true south is generally the most desirable position when maximizing the solar access of buildings constructed on northern latitudes (Goulding, Lewis, and Steemers1992; Holtz 1990; Littlefair et al. 2000). North-facing buildings have the least possible solar access. East and west orientation is problematic because buildings gain too much direct heat in the morning and in the late afternoon. For example, in London, a change in orientation from true south to true west can increase space heating energy use by 16% in passive solar houses and by 9% in conventional homes (Steemers 2003). Due to this significant effect, energy conserving site planning guidelines, including street and building layouts for solar communities was extensively studied in the 1970s and the early 80s (Brown 1985; Center for Landscape Architectural Education and Research 1978; Erley and Jaffe 1997; Hammond et al. 1981; Robinette 1983).

Street orientation usually determines the orientation of houses, especially where structures cover a higher fraction of buildable land (Edminster 2009). In the northern hemisphere, east-west street orientation provides north-south lots, which allows for more south-facing buildings in a neighborhood (Figure 2.3). East-west lots on north-south streets or irregular lots on cul-de-sacs can also accommodate south-facing houses through lot modification and by changing the orientation of the houses (Hammond et al. 1981; Littlefair et al. 2000; Thayer, Jr. 1981).

However, these lot modifications for solar access have rarely been practiced, especially in urban settings where building coverage is usually maximized. Another aspect to be considered is that in hot climates, east-west street orientation may be avoided in order to provide adequate outdoor comfort unless the streets are very narrow when in comparison to the building heights. For example, in Athens (38°N), building height to street width ratio (H/W) need to be at least 4, for Rome (42°N) 3.5 would be the best H/W ratio to minimize sun penetration (Littlefair et al. 2000). In addition to solar access, appropriate street orientations that protect buildings from cold wind contribute to the reduction of heating energy use. Instead of the wind having a penetrating effect on structures, street orientation perpendicular to the wind direction can make the primary air flow above the buildings (Givoni 1998).

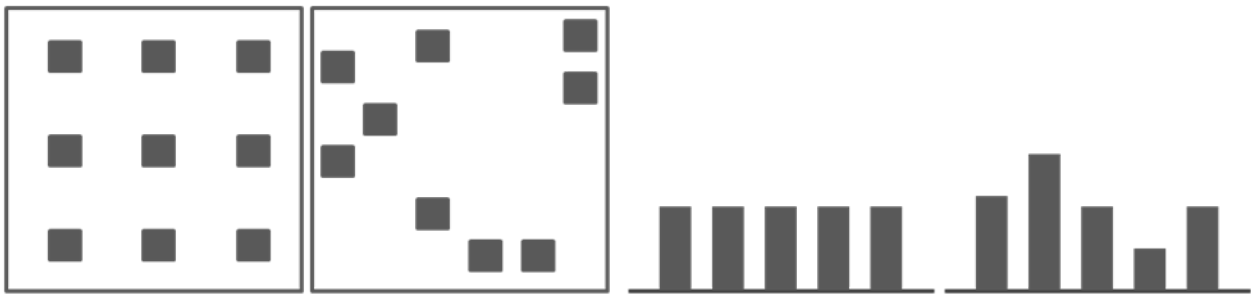
Figure 2.3 Street orientation that maximizes solar access



East-west street orientation (north-south lots) maximizes south-facing homes, which allows for solar access

Building configuration – the patterns of vertical heights and horizontal arrangements —are also important factors that affect solar access. Compagnon (2004) used 3D models to indicate that it is possible to achieve higher passive and active solar potential with optimal layout designs, even in denser environments. Among his four hypothetical designs, the striped configuration with uniform building heights and the stepped slab blocks with variable heights, showed a large increase in the solar potential for denser planning scenarios. Cheng et al. (2006) used 3D simulation to test three parameters of urban forms: forms built with uniform and random horizontal and vertical layouts (Figure 2.4), plot ratio, and site coverage representing a range of different built forms and densities. Cheng et al. (2006) concluded that building configurations with higher horizontal and vertical randomness, less site coverage and more open space were preferable in order to enhance daylight performance and solar potential.

Figure 2.4 Examples of different horizontal and vertical building layouts



Modified from (Cheng et al. 2006)

[SIMULATION MODELING]
Even though many design guidebooks emphasize the importance of site layout, only a few simulation studies were conducted and no empirical research exists on assessing the impact of street orientation with regard to residential energy use. Using simulation for a typical single-family house located in Quebec City, Paradis et al. (1983) argued that the optimal street orientation (20 degrees east of south) could reduce the maximum instantaneous heating load by 24 to 70% (maximum reduction for the windy day) and could also reduce annual household energy use by 16.5% (the total reduction rate is less than that in heating load due to the trade-off of solar gain in cooling load). Littlefair (1998) and Littlefair et al. (2000) cited NBA Tectonics' study (1988) that assessed the impact of site layout on passive solar housing on low and medium density housing in the U.K. Passive solar housing with an appropriate orientation could save 11% on the space heating load but these savings were decreased by less than half in the dwellings with non-optimal street layouts. No empirical research has been conducted with regards to the relationship between street orientation and residential energy use.

Summary and Recommendations

- Few simulations and empirical studies were conducted to assess the impact of site layout (street orientation and building configuration) on residential energy use.
- More empirical studies and the development of simulation tools for quantifying the impact of various layout variables (street orientation, horizontal and vertical building layouts, site coverage) on residential energy use would contribute to filling the literature gap in this field.
- Research findings should be applied to craft policies and regulations that foster energy-conserving site layout designs and should be more readily used in the real development plans.

Vegetation and surface coverage

Tree planting is known as an effective means of reducing house energy demand. Trees reduce cooling loads because: tree shade moderates solar access to the building façade and the ground surface; they absorb solar radiation and cool the air by evapotranspiration; vegetation on the windward side of buildings modify air flow to promote natural ventilation; trees on the street and open spaces and vegetated surfaces contribute to moderating the urban heat island effect by reducing the air and surface temperatures. Due to these various anticipated positive effects on energy savings, the effect of trees on reducing energy use has been intensively studied in comparison to other urban form variables.

However, trees do not always save energy. Trees may increase the heating load by blocking solar radiation. A lack of consideration of climate and misplacement of trees can lead to an increase in heating and cooling energy use (Láveme and Lewis 1995). Thayer et al. (1983) found that there is a significant net increase in annual energy costs when street trees are placed in the zone directly south of a solar house. In Sacramento, the average benefit for each tree planted to the west of houses ($120) is estimated to be nearly three times greater than the average benefits for all trees planted through the entire shade tree program ($39) (Hildebrandt and Sarkovich 1998). Proper tree selection and placement considering growth rate and crown shape can improve seasonal solar access and wind patterns for maximizing energy savings (Heisler 1986b).

Considering all the mixed effects, tree planting appears to have a positive net effect in saving space-conditioning energy. Heating energy savings due to the trees′ wind-shield effect is found to exceed the heating penalty from the shade (Simpson 1998; Simpson and McPherson 1998). Moderate to high tree density with a combination of deciduous and evergreen trees perpendicular to the wind direction is most desirable for maximizing wind-shield effect (Hammond et al. 1981). Heisler (1986b) finds that the overall maximum annual energy savings in conventional detached houses due to proper tree planting is estimated about 20 to 25% across the different climate and house and tree conditions. In Chicago, increasing tree cover 10% or planting about three trees per lot is estimated to save annual heating and cooling costs by $50 to $90 per dwelling unit (McPherson et al. 1997). Energy conserving planting guidelines were developed in the 1970s and the early 1980s and specific instructions were made with regards to tree types, size, distance and orientation to the house that would provide optimal solar access, solar control and wind buffer for different climates (Erley and Jaffe 1979; McClenon and Robinette 1977; McPherson 1984; Moffat and Schiler 1981).

Among various energy saving effects, the cooling impact from tree shade has been received the strongest attention. For most climates, placing deciduous trees on the west side of houses is widely recommended because they control solar radiation in summer but allow it during winter. Under clear skies a mid-sized sugar maple tree on a south-facing wall reduces irradiance in its shade by about 80% when in leaf, and by nearly 40% when leafless (Heisler 1986a). The importance of tree shading is more stressed in hot climates. Parker (1987) reports that the walls shaded by shrubs were 24° to 29°F cooler than uncovered walls during periods of direct sunlight and are significantly cooler even during periods without direct solar radiation. In addition to a direct cooling effect from tree shade, indirect energy savings due to evapotranspiration is found to be even three to four times greater than the cooling effect that direct shade has (Huang et al. 1987).

Supported by these research findings, tree planting principles were implemented in municipalities since 1990, for example, the Sacramento Municipal Utility District's (SMUD) shade tree program. Tree planting initiatives have proven to be cost-effective from the energy efficiency perspective especially in hot and dry regions like in Sacramento (Hildebrandt and Sarkovich 1998; McPherson and Rowntree 1993; McPherson and Simpson 2003). With focused attention, the effect of trees on reducing energy use has been intensively studied through experiments, simulations and by empirical research. However, it is challenging to compare the results of the study because the experimental settings or the assumptions of each model are different with regards to tree size and type, house condition and climate.

[EXPERIMENT]

The effect of vegetation on saving cooling energy use has been most actively measured by experimental settings. Several experiments show that the effect of trees is estimated to save in the range of 25 to 80% of cooling energy within different climates, house conditions, and vegetation settings. In Tucson, Arizona, McPherson et al. (1989) conduct an experiment with three similar 1/4 scale model buildings with different landscaping: turf, rock mulch with a foundation planting of shrubs, and rock mulch with no plants. They claimed that the house with no vegetation consumed 25% more electricity for air-conditioning than the house surrounded with turf and 27% more electricity than the house with shrubs. In Sacramento, California, Akbari et al. (1997) also measure cooling energy use in two homes (the one with eight large and eight small shade trees and the other with no trees) and found a 30% reduction of the cooling energy use due to the effect of tree shade. Through the energy analysis of an insulated mobile home in Miami, Florida, Parker (1983) shows that proper landscaping can reduce energy use for air-conditioning by more than 50% (5.56kWh to 2.28kWh in the morning and 8.65kWh to 3.67kWh for afternoon peak hours) during warm summer days. In Beauregard, Alabama, during April to September of 2008, Laband and Sophocleus (2009) state that in comparison to buildings exposed to full sunlight, building situated in dense shade use 2.6 times less electricity for cooling (about 62% energy saving) to 72 °F. DeWalle et al. (1983) reports even greater energy savings in central Pennsylvania. For a mobile home in a forest site a seasonally-averaged estimated saving for air conditioning is 75%.

Using similar approach, heating energy savings due to the trees' role as windbreak is measured and is reported to have a range of savings from 3 to 40 % in North Dakota, Pennsylvania, and New Jersey (Heisler 1986b; McPherson and Rowntree 1993). The majority of energy saved is brought about by reducing cold air infiltration. For example, in central Pennsylvania, placing a small mobile home at about one tree height (3m) from a windbreak results in reducing winter space heating up to 18% (DeWalle and Heisler 1983). However, the benefit of heating energy saving from a tree windbreak can be offset by the increasing demand of space heating due to the tree shade. DeWalle et al. (1983) report that energy savings from the deciduous windbreaks are measured as only 8 percent of the energy saved and heating energy demand rises 12 percent when a dense pine forest provides more shade. Overall, the effect of tree windbreaks and the counter-effect between tree shades and windbreaks have not been thoroughly examined across various climates with experimental settings compared to research on the tree's effect on cooling energy savings.

These experiments provide meaningful real-world results to develop landscape design strategies. However, less controlled settings with small sample sizes (usually one or two options in addition to the control and one sample to represent each category) limits the reliability of the results. Also, it is difficult to consider these studies as a representation of each case because only few experiments have been conducted for each climate and house conditions. This lack of representation should be supplemented by more experimental cases and simulation studies. Instead of comparing the experimental results conducted from various settings, the results from these experiments can be more useful for validating other types of studies (simulations) with similar settings.

[SIMULATION MODELING]

In comparison to the experiments, simulation is an effective approach to examine the effect of trees by controlling other variables such as tree configuration, housing conditions, and climate. Building energy analysis tools such as DOE-2, SPS (Shadow Pattern Simulator) and MICROPAS have been used to simulate the effect of trees on energy use. DOE-2 is free building energy simulation software that was developed by James J. Hirsch & Associates in collaboration with the Lawrence Berkeley National Laboratory (LBNL). DOE-2 simulates hourly-based building energy performance depending on climate, building envelope, equipment use and occupant behavior. The effects of trees are implemented by altering weather files that incorporate the changes of microclimate due to trees and modifying the building description file that take into account the surrounding tree canopy. MICROPAS is a commercial building analysis tool but requires shading data from SPS in order to incorporate the effect of tree shade. The lookup table approach that adopts simulation results for typical configuration is also used for scaling up the analysis from the site to a broader scale (e.g. neighborhood or larger areas) (Simpson 2002).

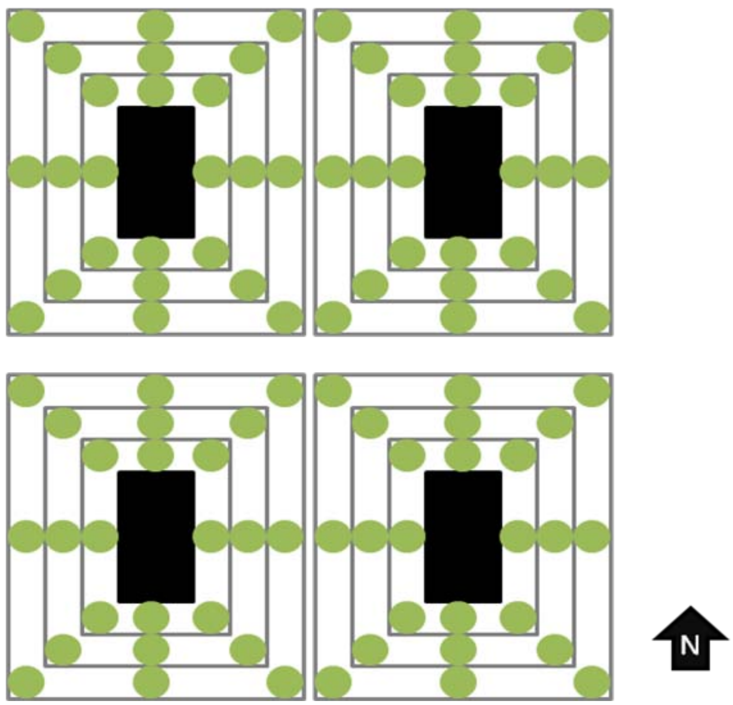
Urban Heat Island Group at the Lawrence Berkeley Laboratory is one of the most active research groups that examine the effect of vegetation and surface coverage (albedo) on microclimates and residential energy use ranging from a single building up to a global scale. Using DOE-2.1C, Huang et al. (1987) examined the potential impact of trees in reducing summer cooling loads on residential buildings. DOE-2.1C considers tree canopy to be exterior building shade with a determined geometry and transmissivity. It calculates potential energy savings using an estimated reduction of solar gain, wind speed, and evapotranspiration. They found that trees have a significant impact on reducing cooling loads whether or not they are optimally located. Without considering optimum shading an additional 25% increase of the tree cover was estimated to save 40% of the annual cooling energy use for an average house in Sacramento, about 25% in Phoenix and in Lake Charles. With optimum shade settings the savings were further increased to more than 50% in Sacramento and 33% in the other two cities. In four Canadian cities – Toronto, Edmonton, Montreal, and Vancouver, Akbari and Taha (1992) used a similar approach to investigate the effects of trees and white surface on heating and cooling energy use. In the case of Toronto, when increasing the vegetative cover of a neighborhood by 30%, which corresponds to about three trees per house and increases the albedo of the houses by 20% (from moderate-dark to medium-light color), the heating energy savings was about 10% in urban houses and 20% in rural houses while cooling energy saving was greater—40 and 30%. The annual savings in heating and cooling costs were greater in rural areas; the savings ranged from $30 to $180 in urban areas and from $60 to $400 in rural zones. Rosenfeld et al. (1998)

used a similar approach for Los Angeles, California and reported that tree shades are most effective in reducing building energy use, but the savings due to urban heat island mitigation through evaporative cooling are also significant. Avoiding peak power for air conditioning can reach about 1.5 GW in Los Angeles (more than 15% of the city's air conditioning) and 25 GW in the entire US, with potential annual benefits of about US $5 B by the year 2015. Akbari et al. (2001) estimated that about 20% of the national cooling demand can be avoided by implementing a large-scale cool communities program that includes cool surfaces (roofs and pavements) and urban trees. Using the results from Rosenfeld et al. (1998) and other previous studies, Akbari (2002) estimated CO_2 emissions reduction due to the direct effects of shade trees in reducing building energy use as well as indirect effects of community cooling.

McPherson and Simpson of the USDA Forest Service have led many simulation studies to investigate the impact of trees on space-conditioning energy use (both heating and cooling) using SPS and MICOPAS. Assuming the typical one story ranch home in Madison, Salt Lake City, Tucson and Miami, McPherson et al. (1988) simulated the effects of vegetation on heating and cooling energy use via two paths: by irradiance reduction and by wind reduction. Irradiance reduction has shown a negative impact in cold climates but could be favorable in hot climates. In Madison and Salt Lake City, dense shade (from conifers) increased annual heating costs by as much as $128 (21%) and $115 (24%), but the shade from leafless deciduous trees was less significant. However, these two cities located in cold climates could benefit from wind reduction. A 50% wind speed reduction reduced annual heating costs by $63 (11%) in Madison and $36 (9%) in Salt Lake City. However, the effects are exactly opposite in cities with temperate and hot climates. A 50% wind reduction increased annual cooling costs in Tucson by $81 (23%) and by $68 (17%) in Miami. Dense shade on all surfaces reduced annual space cooling costs by 53% - 61% ($155 - $249) and peak cooling loads by 32% - 49%. It was interesting that cooling loads were most sensitive to shade on the roof and the west wall, while heating loads were most sensitive to shade on the south and east walls. The results suggest that designers can balance solar access and control by planting trees to shade the roof and west wall while minimizing the winter shade on the south and east walls. However, designers should be careful in generalizing the landscaping strategies due to the complex interactions between shade and wind reductions, especially in temperate climates. For a range of building insulation levels and climate zones in California, Simpson and McPherson (1996) continued to examine the relative effects of different tree orientations on residential air conditioning and heating energy use. In most places within California, cooling load reductions were always greater than increased heating loads associated with shade from south side trees in winter, except in climates with little air-conditioning demand. For all climate zones and insulation levels considered, tree shading a west wall showed the largest savings, both annual (kWh) and peak (kW). The next largest savings were Southwest (annual and peak) and East (annual only). Three trees, two on the west, one on the east side, reduced annual energy use for cooling by 10 to 50 percent (200 to 600 kWh, $30 to $110) and peak electrical use up to 23 percent (0.7kW). Air-conditioning savings, both peak and annual, were larger in un-insulated buildings, warmer climates and percentage savings were larger in cooler climates and well-insulated buildings.

This relative impact simulation of tree orientation on energy saving is used in the assessment of cost-effectiveness for urban tree planting programs in California (Hildebrandt and Sarkovich 1998; McPherson and Simpson 2003) (Figure 2.5). Simpson and McPherson (1998) evaluated the effectiveness of the Sacramento Shade program by investigating the trade-off between heating penalties and the cooling energy savings from a random sample of 254 residential properties selected from the 20,123 program participants in 1991-1993. Of averaged over all homes, they estimated that 3.1 program trees per property reduced cooling energy use by 7.1% (annual) and by 2.3% (peak) per tree; but a tree also increased the annual heating load by 1.9%. These estimates suggested that a tree has a net savings of $10.00 from the shade by accounting that the annual cooling savings of $15.25 per tree was reduced by a heating penalty of $5.25 per tree. On the other hand, when considering reduced wind speed, an annual cooling penalty of $2.80 per tree and a heating savings of $6.80 per tree were estimated, for to have had a net savings of $4.00 per tree and a total annual savings of $14.00 per tree ($43.00 per property).

Figure 2.5 Example of tree configurations



Since the late 1990s, McPherson and Simpson also began to enlarge the scale of the analysis to measure the regional impact of urban trees on climate and energy savings. Simpson (1998) extended the results from previous simulation studies that assessed tree impacts on the energy saving of a single building to a regional scale. The Sub-Regional Assessment District (SubRAD) was used as a unit of analysis and all of the data for each variable (energy use, number of buildings, building vintages, tree cover, and tree density) was combined for each SubRAD to estimate the variables' impact on space-conditioning energy use in Sacramento County, California. Aiming to develop a more simplified method for simulating a large numbers of houses, Simpson (2002) also developed a lookup table that included energy savings for typical tree types (e.g. size and shape), locations around buildings (tree location by distance and direction from buildings) and the frequency of trees at those locations. This method was evaluated by comparing detailed simulations of 178 homes in Sacramento, California.

[STATISTICAL ANALYSIS]
In contrast with active research efforts using simulation, few studies have investigated the impact of trees on energy savings using actual energy billing data. The biggest barrier is the difficulty of accessing energy billing data with disaggregated form (individual household or dwelling unit) due to the confidentiality of utility customers. For the acquisition of billing data, researchers must obtain an approval from sample households; otherwise researchers must use indirect methods to protect customer information (e.g. aggregation or using pseudo-addresses, etc). Furthermore, it is very challenging to control other factors that affect energy use (e.g. occupant behaviors). Obtaining enough reliable information is uncertain even when collecting information through surveys. In spite of these challenges, empirical research contributes to showing the pattern of the impact of vegetation on energy use.

Láveme and Lewis (1996) first looked at the effect of vegetation density on the space-conditioning energy use (both gas and electricity use) of 101 single family homes in Ann Arbor, Michigan. They used three distinct levels of vegetation density: strata low, medium, and high. Láveme and Lewis reported that the differences in energy use patterns between strata were noticeable, but they were not statistically significant. They surveyed individual homeowners to control appliance/structure and behavior-related factors but they reported that the reliability of information regarding most influential factors remained uncertain. Recently Pandit and Laband (2010ab) also conducted a large-scale empirical study for Auburn, Alabama and reported that tree shade reduces summertime electricity consumption. In addition to shade coverage, dense shade provides a statistically significant reduction in summertime electricity consumption as compared to no shade. However, morning shade in wintertime increases electricity consumption (Pandit and Laband 2010b).

Like simulation research, most empirical studies have focused on the impact of vegetation on reducing cooling energy loads during the summer. A study of evaluating the effectiveness of various energy conservation measures in Phoenix, Arizona, Clark and Berry (1995) included “planting large trees (three trees on average) to shade sunstruck sides of houses” as one of the cooling energy saving treatments. Through their regression analysis it is reported that tree shading has a negative influence on energy use but the effect is not statistically significant at a 10% level. Jensen et al. (2003) measured urban forest leaf area index (LAI) using remote sensing techniques and investigated the relationship between LAI and household electricity use during the summer in Terre Haute, Indiana. Using a simple scatter-plot, they reported the inverse relationship between LAI and summertime energy use but the correlation was not statistically significant. Furthermore, there were no other controlling variables in this study. Donovan and Butry (2009) were also interested in summertime energy use but first examined the relative impact of different tree configurations and the size of tree cover. Using regression analysis on 460 houses in Sacramento, California, they concluded that trees planted in the west quadrant (within 20, 40, and 60ft buffers) and the south quadrant (within 20 and 40ft buffers) significantly reduced summertime electricity use. In contrast, tree cover in the north quadrant (within a 20ft buffer) increased electricity use.

Summary and Recommendations

- In comparison to other urban form variables the effect of trees on reducing space-conditioning energy use, especially cooling energy use, has been intensively studied and implemented in several municipal tree planting programs. Compared to numerous studies using experiments and simulations, much less empirical research has been conducted due to the limited access to energy use data.
- Many experimental, simulation, and empirical research show that tree planting is known as an effective means to reduce cooling and heating energy demand in multiple ways: controlling solar access, evapotranspiration, natural ventilation, moderating urban heat island effect etc. Although trees may increase heating loads by blocking solar radiation, taking all the mixed effects into account, tree planting appears to have a positive net effect on saving space-conditioning energy.
- Experimental research provides real-world observation but their limited sample size and particular experimental settings make the results less representative. The results from experiments can be used for validating the results from simulation or empirical studies (e.g. simulations) with similar settings instead of comparing the experimental results conducted from different settings.

2.1.4 Conclusion and Discussion

Energy efficient site design and neighborhood planning guidelines were developed during the late 70s and early 80s and although insufficient, a fair amount of studies have been published to evaluate the effectiveness of these guidelines. By reviewing the research articles published in peer-reviewed journals from the late 70s to present, a clear trend was observed that demonstrated the enlargement of these study scales. Beyond a single building, researchers have also been interested in the effects of outdoor elements such as: building configuration, neighborhood density, neighborhood layout and vegetation; both in back yards and regional-scale planting.

Many research findings support the hypotheses that urban form variables, across scales: housing type, density (compactness and population/dwelling unit density), street orientation, building configuration and vegetation planting, affect houses' space-conditioning energy use. However, this does not indicate that a certain kind of urban form is universally ideal for reducing houses' space-conditioning energy use. For example: although a compact form blocks solar access, reduces heat transfer and provides shade, which is beneficial to reduce cooling energy demand, it can contribute to increasing heating demand and can also promote an Urban Heat Island effect. The trade-offs for different urban forms in various climates have been discussed in terms of design principles but not many of them have been evaluated through empirical research.

Among the urban form variables reviewed, a large variation was observed among each variable reviewed with regards to the amount/popularity of research. The effect of vegetation on space-conditioning energy use, especially on reducing cooling energy use and mitigating urban heat island, has been most intensively studied. These studies have begun to incorporate more comprehensive approaches that include other environmental and economic benefits such as improving air quality and increasing property value using cost-benefit analysis and life-cycle assessment. On the other hand, the effect of community layout is the least studied. This intensity of research appears to be related to the implementation of the particular design principle. Given the support of the numerous research findings, several municipalities implement their citywide tree planting program (e.g. Sacramento, Los Angeles, Denver, New York, Seattle etc). In contrast, it is rare to find a residential development that considers energy saving community layout (street orientation and building configuration) except for few symbolic communities in an energy crisis.

As for the research methods, simulation studies have been most popular in modeling the impact of urban form variables on space-conditioning energy use as compared to experiments or statistical analysis. This is primarily because simulation provides easy control of other variables and little requirement to collect a lot of data such as occupant behavior and energy use data. For the same reason, empirical studies appear to be less popular due to the difficulties in accessing energy data and collecting data for other variables. Still several researchers in urban planning, forestry and economics have conducted large-scale statistical analysis using empirical data and showed a similar pattern of energy savings/penalties that simulation research has shown. Several experiments were conducted mostly for evaluating the impact of vegetation effect. Readers must understand the results of each study within the context of the methods used, geographic region, climate, and specific conditions. As each study is conducted based on different methods and assumptions, readers should be careful in generalizing or comparing the results of previous studies.

As discussed in the introduction, more interdisciplinary and trans-disciplinary efforts must be made to implement better energy conserving designs, planning and policies across the scales. In addition to the energy efficiency of individual buildings, neighborhood or broader scale research should receive more attention and these studies will facilitate the implementation of energy saving neighborhood design that has a longer temporal and a larger spatial impact on energy use. Both the development of more rigorous neighborhood-scale energy simulation and empirical studies that include physical and natural urban form variables, demographic data and disaggregated billing data will contribute to a more comprehensive understanding of the impact of urban form on residential energy use. Large-scale analysis can also be expanded to account for current associated urban energy issues such as: the impact of urban form variables upon on-site renewable energy generation and zero net energy performance, trade-offs among various energy saving design strategies and cost-benefit analysis and life-cycle analysis encompassing embedded resources and the energy use of different urban form scenarios.

2.2 Urban From and On-site Solar Energy Potential

2.2.1 Introduction

As urban forms affect space-conditioning energy use by influencing solar access of buildings, urban form variables such as housing type, density, street orientation and vegetation settings also have significant influences on on-site rooftop solar potentials. In other words, urban forms have an impact on both *passive* and *active* solar access.

In this chapter, I first review the principles of solar geometry – how the seasonal sun paths affect on-site "active" solar energy systems (e.g. rooftop PVs and solar water heating devices). I also review a few examples of solar laws and regulations. Lastly I discuss urban form attributes that affect on-site rooftop solar energy potentials based on previous research findings.

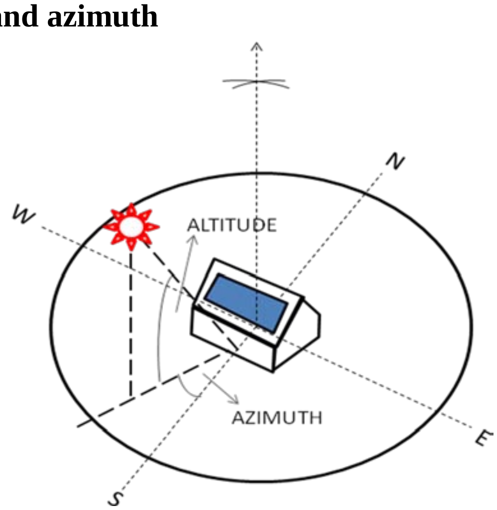
2.2.2 Solar Geometry

Solar geometry is a significant factor for a building's solar access. Because the sun is not a fixed object and moves both throughout the day and throughout the year, solar geometry can be a complex issue, particularly when it is coupled with various urban form metrics. In this chapter, I review some of the key factors in solar geometry that affect solar access of the buildings. I mainly refer to Rob Thayer's study, *Solar Access: "It's the laws!"* (1981) that aimed to provide a manual on California's Solar Access Laws for more effective planning and design applications of solar energy.

Solar altitude and azimuth

Solar altitude is the angle between a horizontal plane on the earth's surface and a line drawn between a point on that plane and the sun. Solar azimuth is the angle between true south and a plane passing through the sun and perpendicular to the horizontal plane on the earth's surface. Solar altitude angle is maximum in summer and minimum in winter. The length of daylight hours is also maximum in summer and minimum in winter.

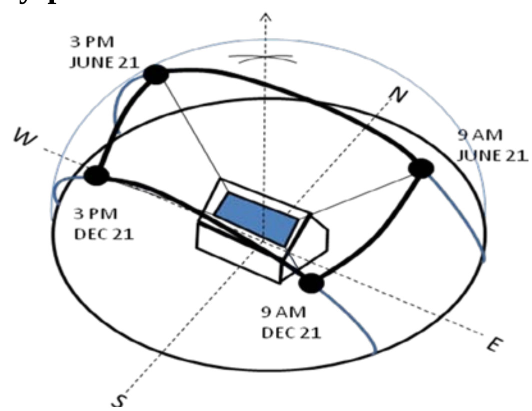
Figure 2.6 Solar altitude and azimuth



Modified the figure from (Thayer, 1981, p6).

Solar skyspace
Skyspace is "a volume and configuration of space in the sky above the solar collector surface which must be kept free of obstruction for a maximum efficiency of the solar collector" (Thayer, 1981, 1). In California, for a solar collector oriented due south, the skyspace is determined by the position of the sun at 9:00 am and 3:00pm, the most critical time of day for maximum heat gain; both on December 21 and on June 21, the most critical dates of the year. (Figure 2.7) The configuration of the skyspace depends on several factors such as: (1) the location and shape of the collector surface, (2) the orientation of the building housing the collector, (3) the slope of the ground around the structure, (4) the function of the collector (water heating, space heating, cooling, etc.), and (5) the latitude of the building site location (Thayer 1981).

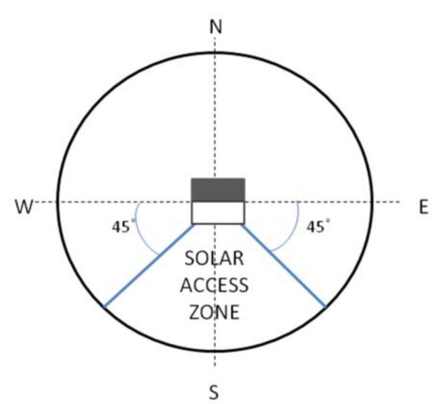
Figure 2.7 Critical solar skyspace



Modified the figure from (Thayer, 1981, p3).

Solar Access Zone
Solar access is "the protection of this skyspace from obstruction by planning, design, policy, and legal methods (Thayer 1981)." In order to take advantage of solar access, it is critical to make sure that intrusion of structures such as trees, buildings, and fences must be outside the skyspace, especially if grounded or planted within the solar access zone. As we see in Figure 2.8, the solar access zone is usually defined as 45-degree lines in plan view from east and west extremities of the solar collector (Thayer 1981).

Figure 2.8 Solar Access Zone



Modified the figure from (Thayer, 1981, p8).

Solar envelopes

A solar envelope is "the volumetric limits of buildings that will not shadow surroundings at specified times (Knowles 1981)." In other words, it is a three-dimensional surface, on a given site, that does not obstruct more than n hours of sun onto adjacent sites (Morello and Rattie 2009)." Knowles (1974; 2003) first introduced the notion of a solar envelope as a zoning device to maximize solar access by regulating development within limits based on the sun's relative motion.

Capeluto and Shavivi (1997) extended the concept of a solar envelope into two kinds of envelopes – (1) Solar Rights Envelope (SRE), which is compatible with Knowles's solar envelope, and (2) Solar Collection Envelope (SCE) calculating the total number of sun-hours obtained by a particular urban three-dimensional surface. The SRE defines the maximum height for a proposed building in order to not compromise the solar rights of its neighbors in a given period of the year; referring to the California solar laws of the 1970s. The SCE defines the lowest possible surface to locate windows and solar collectors so that the solar rights of the proposed building would not be compromised by nearby buildings in a given period of the year. Therefore, the SRE and SCE can determine the upper and lower limit of a 'solar volume' that guarantees the solar access of itself and of its neighbors (Morello and Rattie 2009).

Solar envelopes can be a useful tool to determine a three-dimensional boundary of a proposed plan without obstructing solar access of neighboring buildings, especially in a dense urban environment. However, it is difficult to calculate over extensive urban areas. Furthermore, a solar envelope does not account for energy considerations – defined in terms of discrete numbers of hours of sun or shadow, with little consideration to actual radiation or illumination level (Morello and Rattie 2009).

Iso-solar surfaces

Given these limitations of solar envelopes, Morello and Rattie (2009) proposed the concept of iso-solar surfaces. Iso-solar surfaces are "three-dimensional geometric envelopes which receive equal amounts of solar energy." Iso-solar surfaces also have two kinds (Morello and Rattie 2009):

(1) iso-solar rights surfaces (ISRS) – at each point in space the maximum allowable height of buildable volumes in order to guarantee solar irradiation on adjacent sites,
(2) iso-solar collection surface (ISCS) – at each point the minimum elevation from the ground for collecting a given amount of solar radiation

Compared to Knowles's solar envelopes, which are computed at arbitrary cut-off times, iso-solar surfaces enable the calculation of different irradiation levels and a more accurate assessment of the impact of built form on the accessibility to solar radiation (Morello and Rattie 2009).

2.2.3 Solar Laws and Regulations

Such solar geometry has been incorporated in urban planning legislations in order to guarantee solar access of residents.

New York's Zoning Law

In 1916, New York City adopted the first city-wide zoning regulations enacted as a reaction against the negative environmental impacts caused by excessive density in central Manhattan. It stated that "construction can proceed up to a certain height; then the building must step back from the plotline at a certain angle to admit light to the streets" and "a tower may then carry 25 percent of the plot area to unlimited heights (Morello and Rattie 2009)." Despite the pioneering effort to consider solar environmental impacts of urban development, plans only considered an elementary right for sunshine access from the sky without taking into account real sun paths over the time of the day and of the year (Morello and Rattie 2009).

California's Solar Rights Act

California has been a pioneer in facilitating the use of solar energy since 1976, when it started to provide tax credit for solar energy technologies. In 1978, California adopted the *Solar Rights Act* that went into effect on January 1st in 1979 (Thayer 1981). It aimed to "promote and encourage the widespread use of solar energy systems and to protect and facilitate adequate access to the sunlight which is necessary to operate solar energy system (Anders et al. 2007)."

The Act established the legal right to a "solar easement" that provides access to sunlight across adjacent properties. According to California Civil Code Section 801.5, a solar easement is the "right of receiving sunlight across real property of another for use by any solar energy system." In other words, it is a "legal device to ensure that the skyspace of an individual's solar collector can be protected from intrusion by the structures, vegetation, or other land use activities of another property owner (Thayer 1981)."

However, in reality, obtaining a solar easement is not an easy process. First, the solar collector owner should go through bilateral negotiation with adjacent landowners. Neighboring landowners can refuse to negotiate or to grant a solar easement. In a dense neighborhood, the solar collector owner may need to negotiate with several neighbors to obtain a right to access sunlight. In this regard, the easement can be very costly and time consuming for individual home owners (Anders et al. 2007).

California's Solar Shade Control Act

In addition to the Solar Rights Act, California also enacted the *Solar Shade Control Act* in 1978. The Act aimed to balance the positive effects of planting vegetation for shade with the desire for increased use of solar energy systems, whose performance can be obstructed by shade from adjacent trees and shrubs. The Act provides specific and limited controls of vegetation to ensure solar access to neighboring collectors (Anders et al. 2007).

In spite of the specific regulations, the Act provides only limited protections for solar collector owners because it contains restricted qualifications of solar collectors to be eligible for protections under the Act. To qualify, the collector can be no closer than 5 feet from the property line and must be 10 feet above ground or 3 additional feet back from the property line for every foot lower in height than the 10-foot mark. In addition, the Act did not state if a passive solar home would be protected by the Act. Through the case of *Sher v. Leiderman* in 1986, the court decided passive solar homes and other passive solar systems are not eligible to be protected by the Act (Anders et al. 2007).

Given California's $3.3 billion of financial incentives for solar homes, there will be more conflicts between solar collector owners and their neighbors because the current laws do not fully protect the right of solar access for solar home owners. Furthermore, such limited legal protection may cause a huge loss in the benefits of passive and active solar homes that can save or produce a lot of energy.

2.2.4 Urban Form Variables that Maximize On-site Solar Energy Generation

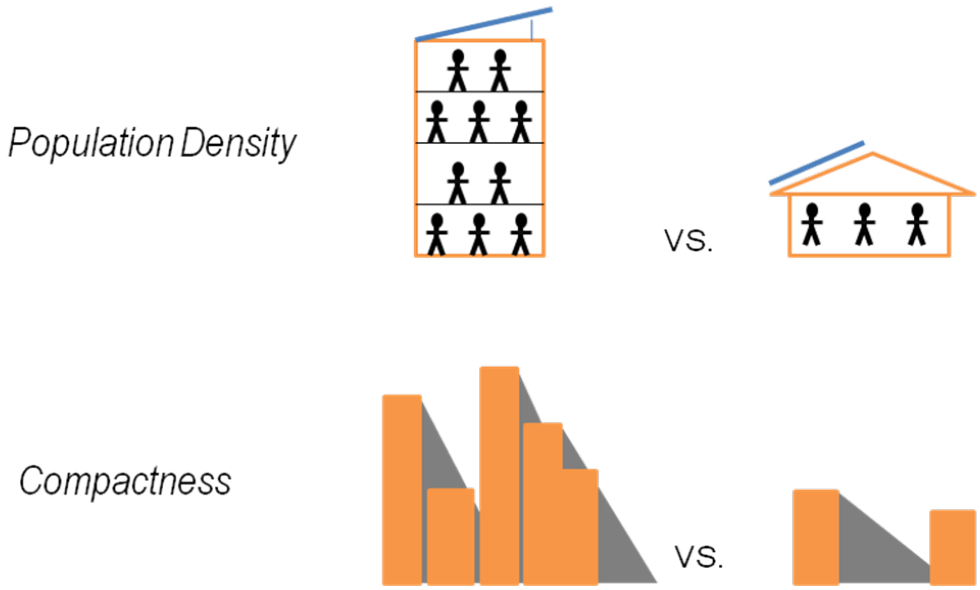
Compared to the impact of urban form on space-conditioning energy use, fewer studies have been conducted with regards to on-site active solar energy systems.

Housing Type and Density

Housing type and density can be discussed together as housing type is generally correlated with density. Urban density, with rooftop solar potential in mind, can be described in two ways: *household or population density* from the planning perspective and *compactness* from the design point of view. A neighborhood with high household/population density often corresponds to a compact neighborhood. For example, San Francisco depicts a relatively high household/population density along with high building coverage across the city. In this regard, solar energy potential per person decreases as density (both household or population density and compactness) increases (Figure 2.9). Rooftop solar potentials in single family housing in low density environment can also be affected by shade from neighboring trees. This concern is discussed later in the chapter.

Previous studies have agreed that housing type and density affect on-site solar potential. Higher household or population density implies that more people live in multi-family housing and apartments, share rooftops (and facades). This association results in smaller available areas for on-site solar energy generation per person (Wiginton et al. 2010). Higher compactness indicates that buildings are "tightly" located on-site and likely results in smaller solar PV potential due to increased shade from neighboring buildings.

Figure 2.9 The impact of population density and compactness on on-site rooftop solar potential



Multi-family housing may appear to be able to generate enough solar energy on-site when accounting for the facades as potential sites for installing Building-Integrated Photo Voltaics (BIPV) and assuming no shade from neighboring buildings. Ordenes et al. (2007) conducted several simulations using the software tool *EnergyPlus* to integrate PV power supply with typical multi-family building energy demand in Brazil. They considered all opaque surfaces of the building envelop similar to BIPV. They found that there is a considerable amount of energy generated from vertical façades even at low-latitude sites in Brazil. This result breaks the common belief that vertical integration of PV is only suitable for high latitude countries. In general, they showed that about 30% of the time buildings generated more energy than the building demand, thus feeding energy to the public grid. However, their study was simulation based and did not consider shades from neighboring structures; it simply calculated the solar potential on all opaque surfaces using *EnergyPlus* software. In this regards, configuration of buildings in dense environment becomes critical determinant of securing solar access.

By accounting the effects of neighboring buildings, O'Brien et al. (2010) examined how the amount of solar energy generated from the roofs and facades vary with housing type and density. They investigated three distinctive neighborhood types: low-density outer suburb with detached houses, medium-density inner suburbs with townhouses, and high-density inner city with high-rise multi-unit residential buildings with optimal building layouts. They found that annual solar radiation per person received by a building in a low, medium and high density neighborhood are 14540 kWh, 5120 kWh and 1370 kWh respectively. In other words, the difference of annual solar radiation per person between low density neighborhood and high density one is greater than ten times.

Community Layout

Given a same density, *building configuration and layout* play a significant role in maximizing solar access both on roofs and facades. In general, the compactness exacerbates solar access of buildings when combined with irregular building heights and narrow street widths (Arboit et al. 2008). However, with optimal building configuration, it is possible to allow more solar access even in a denser environment.

Compagnon (2004) also quantified the potential of façades and roofs located in urban areas for active and passive solar heating, photovoltaic electricity production and day lighting. He compared the façades′ PV potential calculated for the existing area and for four hypothetical urban forms at constant density in Fribourg, Switzerland, and revealed large variations of the potential for solar energy collection on building facades. Regarding the hypothetical urban forms, he set a constant plot ratio (the ratio of total floor area to site area) (2.0), which is relatively higher than that of the local existing form (1.2). The results show that more than 30% of façade area is suitable for passive solar techniques and even more than 50% for active solar and day-lighting techniques even though the existing form of Perolles area was not built with considerations of solar and daylight access. In the hypothetical designs incorporating solar access, striped configuration with uniform building heights and stepped slab blocks with varied building heights showed the large increase of solar potential even in denser planning scenarios.

Street orientation affects solar access of buildings more on façade than on rooftops. Arboit et al. (2008) reported that orientation of city block showed a statistically significant effect on solar radiation received on façade in their study on low-density urban area in Argentina. In case of high-rise accommodation with high density in northern hemisphere (Toronto, Canada), O'Brien et al. (2010) reported their results from simulation (using ESP-r) that south facing facades shows highest annual solar radiation than those with other directions. For example, for the top floor (about 15th floor), south facing façades receive 1002 kWh/m^2 while west, east and north facing facades receive 793, 775 and 397 kWh/m^2 respectively.

Vegetation

Trees are the one of the most significant factors that attenuates rooftop solar radiation, especially in a lower density environment. Trees and vegetation is a mixed bag because they can reduce space-conditioning energy use but also can reduce on-site rooftop solar potentials.

The impact of trees on rooftop solar radiation varies on study sites. Levinson et al. (2009) argue that in their study areas of four Californian cities (Sacramento, San Jose, Los Angeles and San Diego) only 10% of the annual light loss is caused by trees and buildings in neighboring parcels. Although their interests was calculating the impact of trees and buildings only from neighboring parcels, their results appear to show small impact from trees given the fact that their results incorporate tree growth scenarios for next 30 years. On the other hand, Tooke et al. (2011) investigated the impact of trees on residential rooftop solar potentials in the District of North Vancouver (DNV) located within the Metro Vancouver Region of British Columbia, Canada. They reported that trees on average reduce 38% of available solar radiation at residential building rooftops.

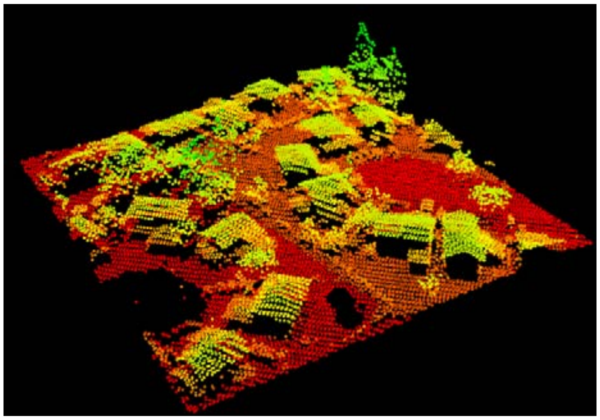
As for the specific impacts from tree structures and configuration, tall trees with large crowns planted on south, southwest and west side of a house can have more impacts on rooftop PV potential in that PVs are usually installed on south, southwest and west facing roof planes. In addition, Tooke et al. (2011) report that they found strong correlations between measures of tree structure (average height, tree height variability, and normalized tree volume). Trees reduce direct radiation in the summer while diffuse radiation appears to be constant throughout the year. In order to secure rooftop solar potential without compromising energy saving effects of trees, proper management in tree heights, crown and configuration appear to be essential.

2.2.5 Conclusion and Discussion

A recent shift towards solar energy adjures planners and designers to more actively seek to integrate on-site solar energy generation into their planning and design. Basic understanding on solar geometry and regulations with regards to "solar rights" were developed in the late 1970s, however, they have not been received much attention until the recent energy crisis. Without more sophisticated understanding in the impact of current urban forms on on-site solar energy potentials, it would be very challenging for cities to maximize their solar energy generation. Furthermore, inappropriately installations of solar devices in existing urban landscapes are likely to bring conflicts between neighbors and inefficient use of taxpayers' money.

Given this challenge, the primary step that researchers need to take is measuring the impacts of various urban forms (e.g. density, compactness, building configuration and structure and tree configuration and structures) on rooftop solar potentials. The optimal building configurations that maximize solar access in dense environment have been studied mostly using simulation approach. Recent studies using LiDAR have aided researchers to investigate those impacts in the real world environment. Another major advantage of the use of LiDAR is that it allows more accurate assessment of the impact of trees on on-site solar potentials in low density environments. As seen in Figure 2.10, LiDAR successfully captures various measurements of tree structures (e.g. heights and crowns), thus contributing to more sophisticated understanding of how trees reduce rooftop solar radiation and how to manage them properly. Identification of those impacted locations can be also useful to prepare the potential conflicts between tree owners and rooftop owners and to promote wise use of taxpayers' dollars.

Figure 2.10 LiDAR point clouds



Data Source: USGS Center for LIDAR Information Coordination and Knowledge (CLICK)

III. Urban Form and Space-conditioning Energy Use: Assessment of the Effect of Urban Forms on Residential Cooling Electricity Use in Sacramento, California

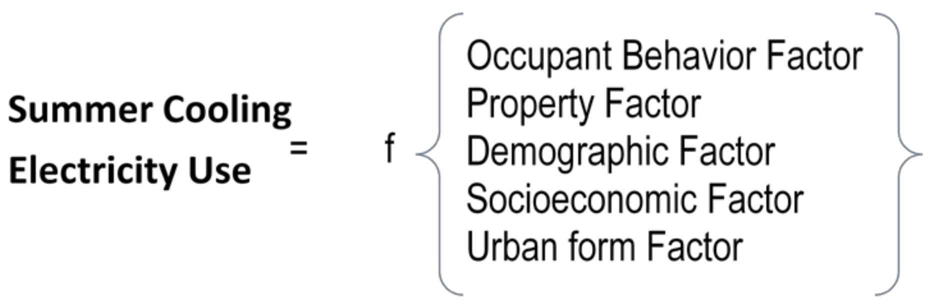
3.1 Introduction

In this chapter, using empirical data, I investigate the association between urban form and space cooling energy use. After the site selection process, for this study, I chose 13,709 residential parcels from the southwest part of the City of Sacramento, CA. Based on the urban design theories described in Chapter II, I created urban form and socio-demographic variables through spatial analysis using GIS and LiDAR data. The variables that I included in this study represent urban form, occupant energy use patterns, property conditions and demographic and socio-economic characteristics. Multivariate analysis is then used to assess the relationship between these variables and summer air-conditioning energy use. This method will enable planners to understand and to quantify how the built environment affects the energy demand of air-conditioning. With the research findings, planners can classify neighborhoods along a spectrum of energy performance.

3.2 Research Design

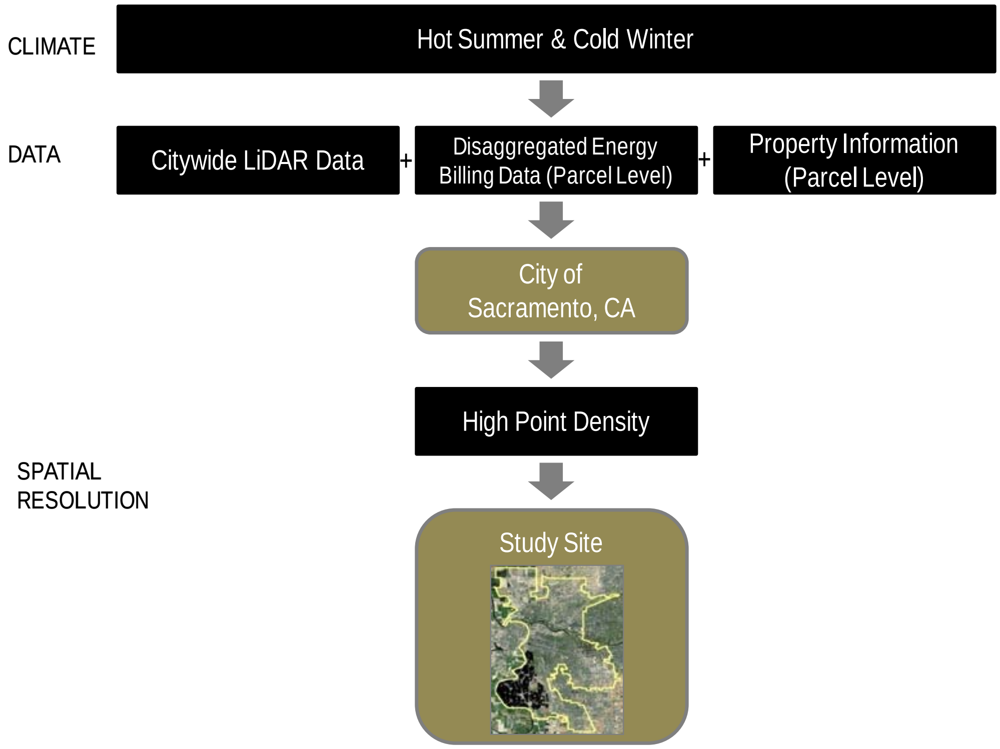
I build a model for estimating summer cooling electricity use as shown Figure 3.1. I assume that summer air-conditioning electricity use is a function of occupant behavior, property conditions, demographics, socio-economic and urban form characteristics.

Figure 3.1 Research design



In order to build a data-rich model that includes both spatial and non-spatial data with good quality and quantity, I designed a site selection process for this study (Figure 3.2). The first criterion for selecting the study site is the region that shows a varied climate with a hot summer and a cold winter. Among these areas, I insure that I can access three main types of data for the site: citywide LiDAR data, disaggregated energy billing data and tax assessor's data with property information. After reviewing several candidates, the City of Sacramento successfully meets these qualifications. However, high density LiDAR data does not cover the entire City of Sacramento, limiting my study site to the southwest part of the city.

Figure 3.2 Site selection process



3.3 Study Area

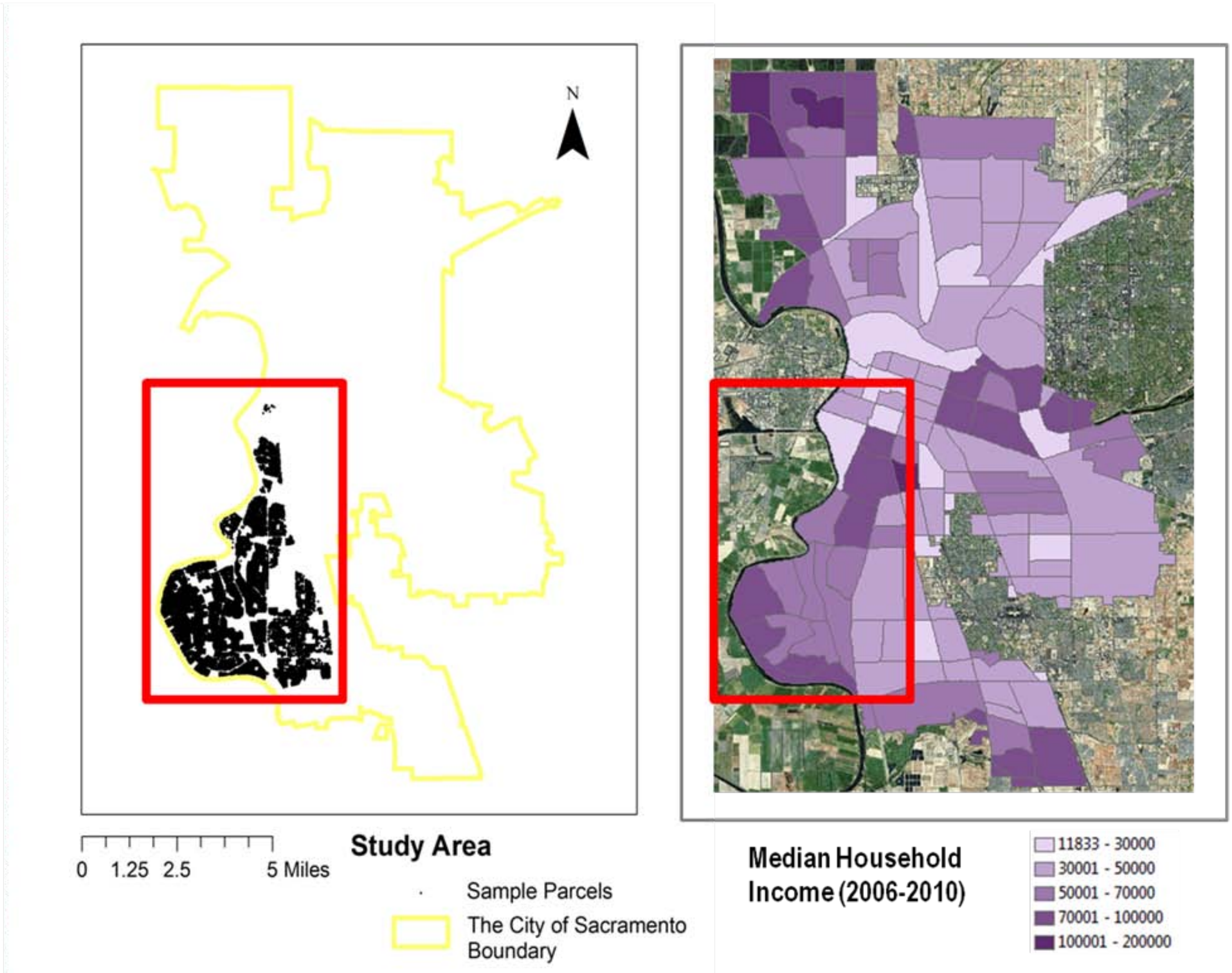
The City of Sacramento is the capital of the state of California and is located in Sacremento County, Northern California (38°33′20″N 121°28′8″W). According to the 2010 Census, Sacramento is the sixth-largest city in the state of California with a population of 466,488 within a land area of 97.92 square miles (US Census Bureau 2012).

Sacramento’s climate is chacterized as Mediterranean, represented by wet mild winters and hot, dry summers. Sacramento’s climate is relatively mild (the 12-month average temperature is 61°), but it shows a relatively large temperature range between the summer and the winter. The average low temperature in January is 38° while the average high temperature in July is 93°. On average, 74 days a year are above 90° (City of Sacramento 2012).

Throughout the year, most of the weather is sunny in Sacramento and the city is ranked as one of the top ten sunniest cities in the U.S (City of Sacramento 2012). From June through September, Sacramento is ranked as the sunniest location. In July Sacramento records an average of 14 hours and 12 minutes of sunshine per day, which is equal to about 98% of the possibile sunshine (National Climate Data Center 2011). The sun shines approximately 78% of the year and it only rains about 58 days during the year; from November to March totaling approxiately 17.5". Snowfall is extremely rare.

Figure 3.3 shows the maps of the study area with the location of sample parcels and the median household income of the site. The study area is about 17 square miles and is located in the southwest part of Sacramento. As we see the map of median household income from 2006 to 2010, this area shows a range of socioeconimc status.

Figure 3.3 Study area



3.4 Data Review

3.4.1 Variables and Data Sources

This section describes the data used and the logic and process of creating variables. I group all explanatory variables into five factors: occupant behavior factor, demographic & socio-economic factor, property factor, urban form factor I (community layout) and urban form factor II (land cover & vegetation) (Table 3.1).

Table 3.1 Description of predictors and data sources

Factor		Variables/ Dummies	Type	Level	Source
Occupant Behavior (Control)	*Energy Use Baseline*	Average Electricity Use in Spring and Fall	CON	Parcel	2008 SMUD
Demographic & Socioeconomic (Control)	*Race /Ethnicity*	Percentage of White	CON	Block	2010 Census SF1
		Percentage of Black			
		Percentage of Asian			
		Percentage of Others			
		Percentage of Hispanic			
		Racial Diversity Index	CON	Block	Calculated using 2010 Census SF1
	Age	Percentage of Under 18	CON	Block	2010 Census SF1
		Percentage of Over 18			
	Wealth	Median HH Income	CON	Track	Census 2010 - ACS 5yr
		Estimated value	CON	Parcel	
		Home ownership: Y N	CAT	Parcel	
	Education	Percentage of Less than high school graduate			
		Percentage of High school graduate			
		Percentage of Some college and associate degree			
		Percentage of Bachelor's degree and above	CON	Track	Census 2010 - ACS 5yr
Property (Control)	*Vintage*	House year built: Before 1960 1960 to 1983 After 1983	CAT	Parcel	Tax Assessor Data
	House Size	lot size (sq.ft)	CON	Parcel	Tax Assessor Data
		total floor area (sq. ft)	CON	Parcel	Tax Assessor Data
		Number of stories	CON	Parcel	Tax Assessor Data
		Number of bed rooms	CON	Parcel	Tax Assessor Data
		Number of bath rooms	CON	Parcel	Tax Assessor Data
		Number of rooms	CON	Parcel	Tax Assessor Data
		Garage (sq. ft)	CON	Parcel	Tax Assessor Data
	Housing Type	Subdivision Non-subdivision Two single family unit Duplex Halfplex Planned unit development	CAT	Parcel	Tax Assessor Data
	Pool	Pool: Y N	CAT	Parcel	Tax Assessor Data

	Roof Type	Rooftype: 1 (Wood) 2 (Wood shak/ Shingles) 3 (Composition Shingles)	CAT	Parcel	
Urban Form I	*Density*	Dwelling unit density (1 acre)	CON	Parcel	Tax Assessor Data and GIS
		Population density (1 acre)	CON	Parcel	
	Orientation	Street orientation	CAT	Parcel	GIS
		EW NS NWSE NESW			
Urban Form II	*Land Cover*	Ratio of green space	CON	Parcel	US Forest Service and GIS
		Ratio of water body	CON	Parcel	LiDAR Data and GIS
	Vegetation	Sum of tree heights with configuration: N_30ft S_30ft E_30ft W_30ft N_60ft S_60ft E_60ft W_60ft	CON	Parcel	LiDAR Data and GIS

*CON: Continuous variables
*CAT: Categorical variables
*Lightly colored predictors were calculated but not included in the model because inclusion of all variables results in strong collinearity in the model. For example, the rest percentage of population over 18 is equivalent to the percentage of population under 18 because the sum of both variables is 100%. Similarly, higher percentage of white population is strongly correlated with the lower percentage of Asian population.

Occupant behavior & System Efficiency

In order to represent the occupant behavior of baseline energy use, I include the average monthly electricity use for the fall and spring months (March, April, September and October). In addition, this variable possibly captures the effect of energy system efficiency in the house, such as: the energy efficiency of a refrigerator, lighting, television, electric cooking devices etc. Using a broad definition, I consider the energy efficiency of electric devices a part of occupant behavior since occupants can select whether they want to use energy efficient devices or not.

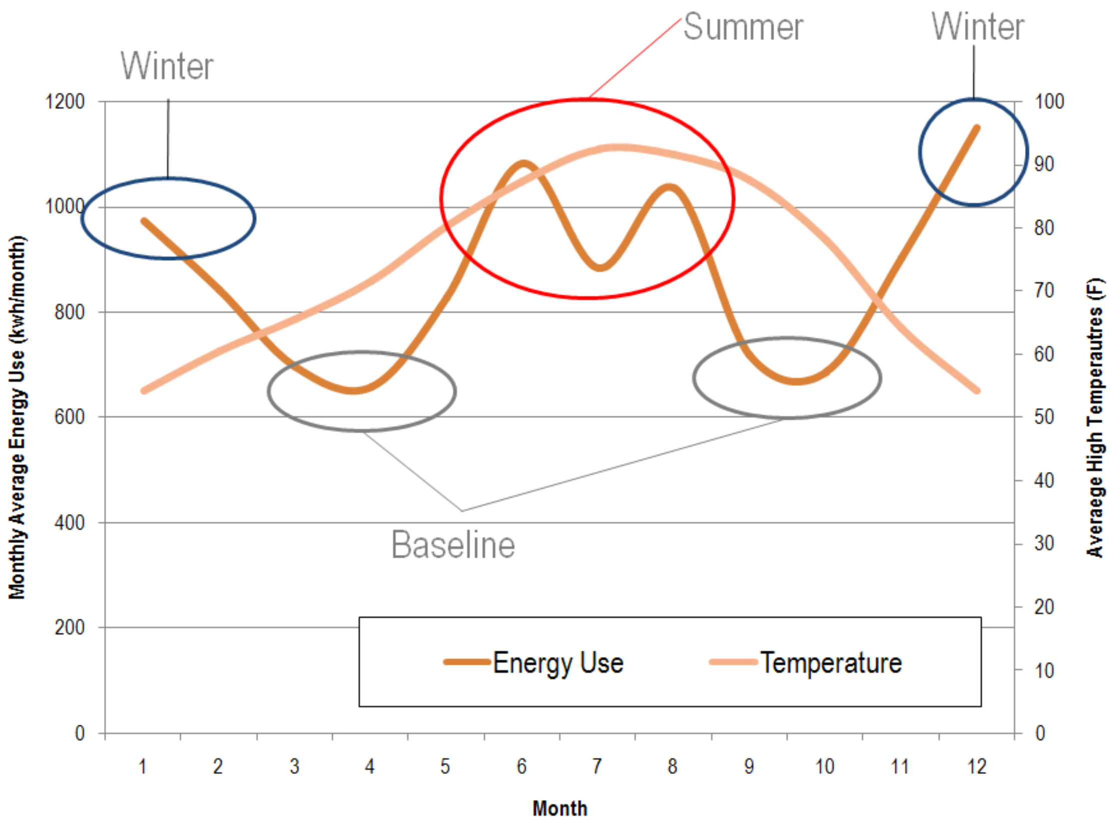
I create the baseline energy use variable using the Sacramento Municipal Utility District's (SMUD) electricity billing data for 2008. The original dataset contains parcel-level monthly electricity use (kWh) with the average billing day, number of billing months and APN. For this study, in order to select the units that are occupied and use energy regularly, I select parcels where there are more than 28 billing days and 12 billing months.

Figure 3.4 illustrates the pattern of the average monthly electricity use for a parcel in 2008 along with the average monthly high temperature in Sacramento (measured at the Sacramento Executive Airport during 1981 – 2010). It appears that June, July and August show summer peak electricity use and December and January represent winter peak electricity use. Worth noting here is the fact that July electricity use is about 150 to 200 kWh lower than those of June and August even though July shows the highest temperature record throughout the year. I suspect this pattern results from units being vacant in July during the vacation period. I use the average monthly electricity in March, April, September and October as a baseline. Using this baseline I create a response variable: the average monthly summer electricity used for cooling. I estimate it by subtracting the average monthly baseline electricity use from the average monthly electricity use for summer, assuming that additional electricity use during summer and winter stems from space conditioning.

$$P_{cool} \approx \frac{P_6 + P_7 + P_8}{3} - \frac{P_3 + P_4 + P_9 + P_{10}}{4}$$

Where,
P_{cool} : the average monthly summer electricity use for cooling
P_i : the electricity use in ith month.

Figure 3.4 Average monthly electricity use for a parcel and average high temperature in Sacramento



Demographic and Socioeconomic Characteristics
While many variables are generated for individual parcels, I create all demographic and socioeconomic variables at an aggregate level as they are derived from US Census data. Using GIS analysis, I create race/ethnicity and age variables at a census block level from the 2010 Census Summary File 1. Income and education attainment are derived from the 2006-2010 five-year estimate of the American Community Survey - at the census track level. Since I create these variables from aggregated data (i.e., census block and tracts), I evaluate a possible margin of error and ecological fallacy, which is "a relation identified between macro-level does not automatically translate into the same relation at the micro-level models (Jones and Duncan 1995; Overmars and Verburg 2006)" in the section 3.6.2.

Property Characteristics
Property information from 2007 is obtained from SMUD. The dataset includes a wide range of fields that specifically describe housing size, type, the assessed value, year built, homeownership etc. for all parcels in Sacramento. This information is also publically accessible through the Assessor Parcel Viewer of the County of Sacramento (http://assessorparcelviewer.saccounty.net/GISViewer/Default.aspx).

In order to best represent the year built, I create three categories from original continuous variables: a house built before 1960, one built between 1960 and 1983 and one built after 1983. These categories are based on Costa and Kahn's (2010) finding that building codes in California have been in effect for houses built since 1983. Homes built in the 1970s and early 1980s are for the most part energy inefficient compared to houses built before 1960 as the price of electricity was low during that time. Table 3.2 supports the logic of the categorization by outlining major energy efficiency changes in homes by vintage years.

Table 3.2 Major energy efficiency changes in electric utility service area homes by vintage years

Year Built	Major Energy Efficiency Changes	Expected Increase in Energy Consumption Relative to pre-1950
1950s and earlier	43% of homes have AC system that is less than 6 years old in 2008 47% of electric homes have a furnace that is less than 6 years old in 2008 24% of homes have single pane windows in 2008	
1960s	More efficient air-conditioning (higher SEER) introduced 22% of homes have AC system that is less than 6 years old in 2008 31% of electric homes have a furnace that is less than 6 years old in 2008 23% of homes have single pane windows in 2008	- + +
1970-77	26% of homes have AC system that is less than 6 years old in 2008 10% of electric homes have a furnace that is less than 6 years old in 2008 Forced air furnace with ducts become more common among electric homes 40% of homes have single pane windows in 2008	+ + + +
1978-83	California energy efficiency standards are introduced in 1978 Better roof and wall insulation (lower U-Factor) Central AC with ducts becomes common in 1980s 19% of homes have single pane windows in 2008	- - + -
1984-91	More efficient heat pump (higher HSPF) More efficient air-conditioning (higher SEER) 8% of homes have single pane windows in 2008	- - -
1992-98	Better wall, raised floor, and duct insulation (lower U-Factor) More efficient air-conditioning (higher SEER)	- -
1999-2000	More efficient air source heat pump (higher HSPF) More efficient water heating (higher energy factor)	- -
2001-03	Less duct leakage (higher duct leakage factor) More efficient permanently installed lighting	- -
2004-05	More efficient water heating (higher energy factor)	-
2006 and later	More efficient heat pump (higher HSPF) More efficient air-conditioning (higher SEER) More efficient permanently installed lighting	- - -

Source: 2005 Residential Table – Vintage Values, p. B-12 in California Energy Commission's 2005 Residential Compliance Manual; Residential Compliance Manuals from 1978 to the present; Consol's "Meeting AB-32 Cost-Effective Greenhouse Gas Reductions in the Residential Energy Sector," August, 2008; 2005; 2008 electric utility Home Energy Survey, restricted to single family homes; Costa and Kahn (2010), p. 28.

Urban Form Characteristics

Urban form variables are derived from spatial analyses using GIS and LiDAR data. I classify variables that represent urban form characteristics into two groups: community layout and land cover & vegetation. First, urban form factor I (community layout) includes population density, dwelling unit density and street orientation. Urban form factor II (land cover and nearby vegetation) includes green space density, water body density and the sum of tree heights with their configuration from buildings. The following section describes how I extract those urban form variables using various spatial analyses.

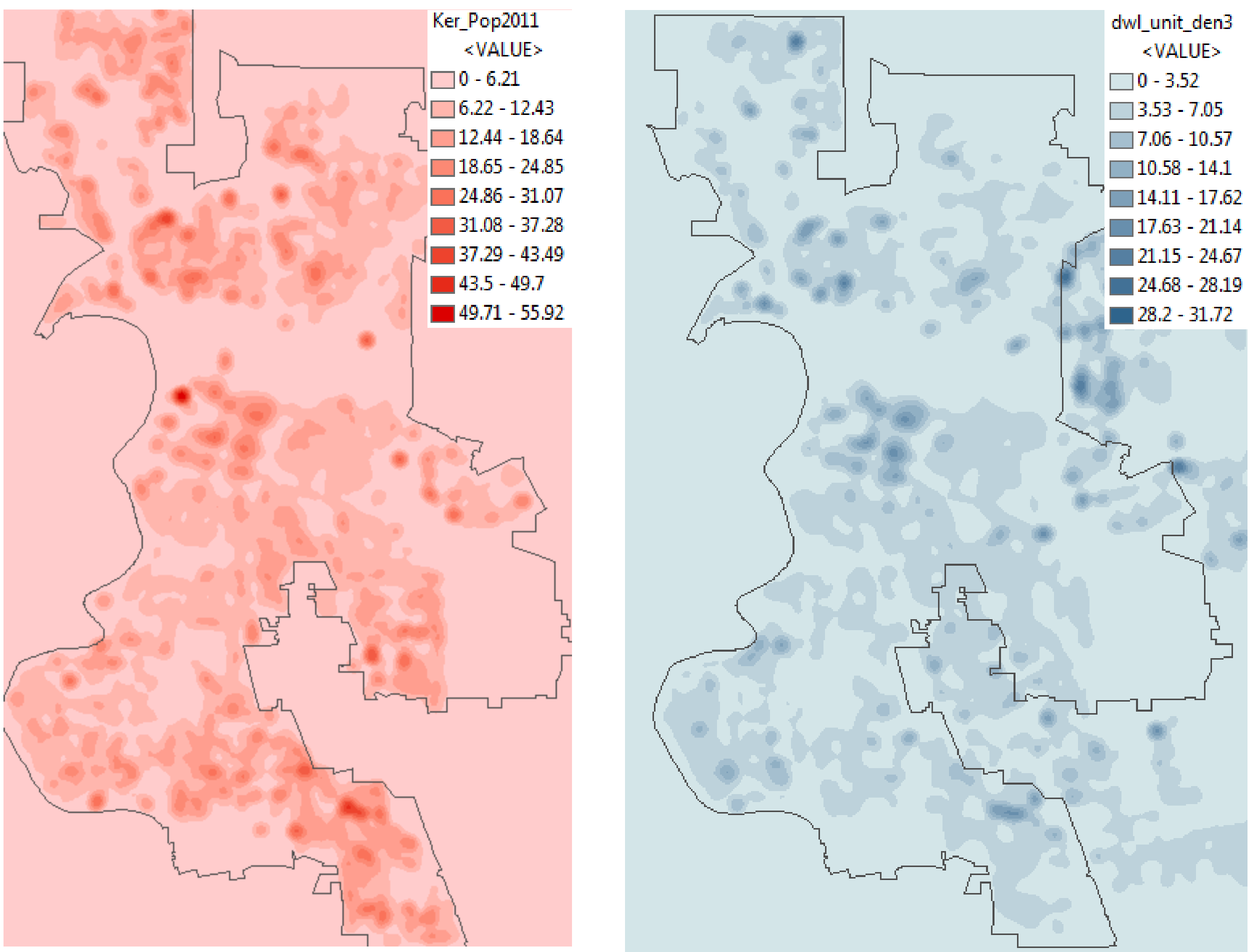
3.4.2 Extracting Variables using Spatial Analysis

In addition to variables directly derived from the table format, I generate many variables of interest using spatial analysis. A discussion follows on how I measure those variables and address important methods and challenges during data processing.

Density

I calculate population and dwelling unit density per acre from each sample parcel in the study area. I use Kernel Density, a built-in function of Spatial Analyst in ArcGIS. Kernel Density "calculates a magnitude per unit area from point or polyline features using a kernel function to fit a smoothly tapered surface to each point or polyline (ESRI 2011a)." I first convert the 2010 Census block population and the number of units in parcels from tax assessor's property data into points because the Kernel Density tool only handles point or poly line features. By kernelling a quarter mile radius, I calculate population and dwelling unit density per acre for every pixel in Sacramento (Figure 3.5) and assign them to the sample parcels.

Figure 3.5 Calculating population and dwelling unit density per acre for individual parcels in residential area

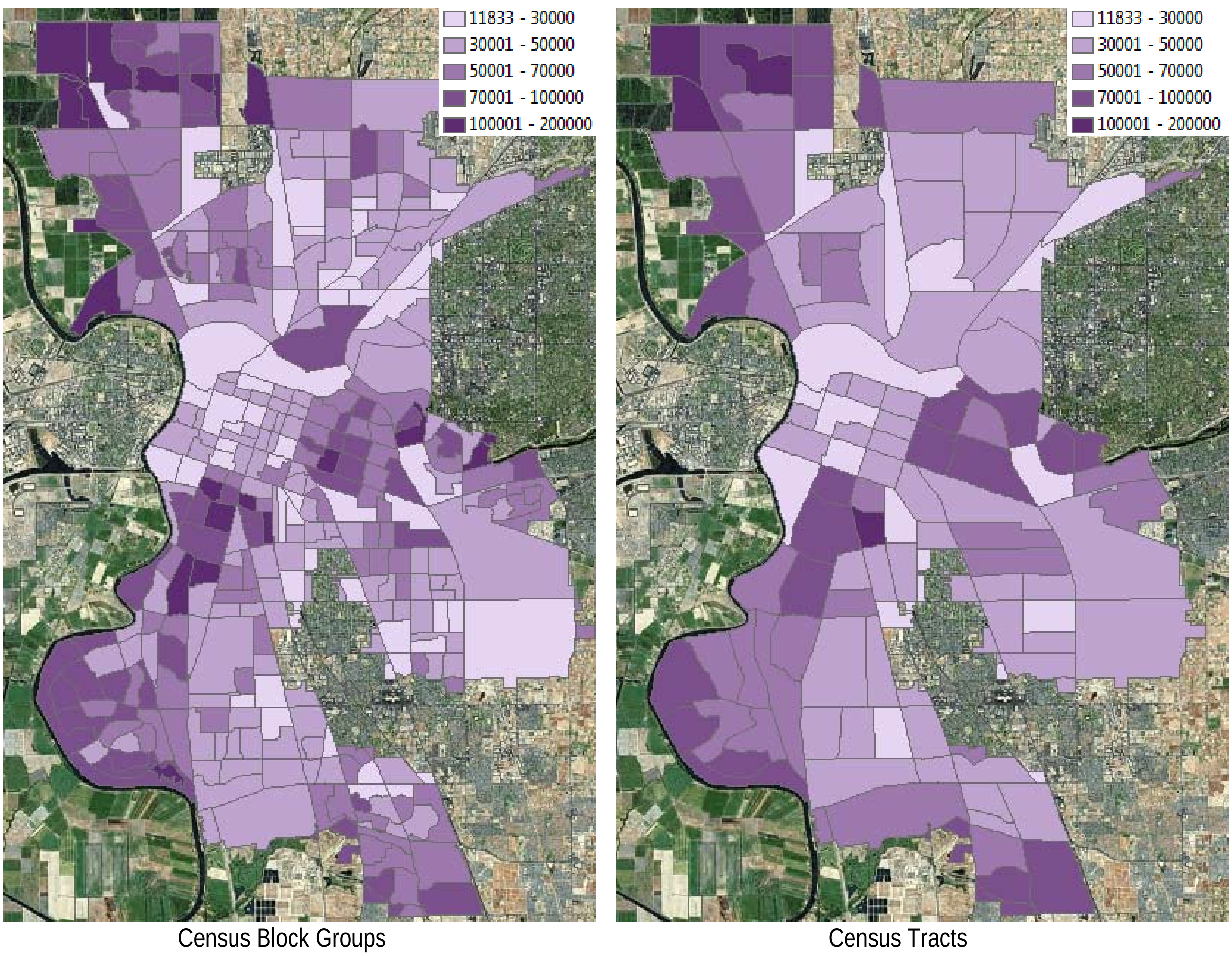


Population Density   Dwelling Unit Density

Median Household Income

Median household income is included as one of the major socio-economic variables. I assume that median household income can represent the economic status of the occupants, which partially explains occupants' energy use patterns. The most disaggregated level data that is publicly available for median household income is the block group level from the 2010 five year estimates of the American Community Survey (ACS). ACS is the replacement for the long form sample data from the previous decennial census (ESRI 2011b). The subjects that ACS includes are similar to the previous long form (e.g. Summary File 3, SF3). Figure 3.6 shows maps of the median household income in a block group level (left) and in a census track level (right). As shown, the block group level estimates depict more disaggregated information than the census track level.

Figure 3.6 Median household income from 2010 five year American Community Survey



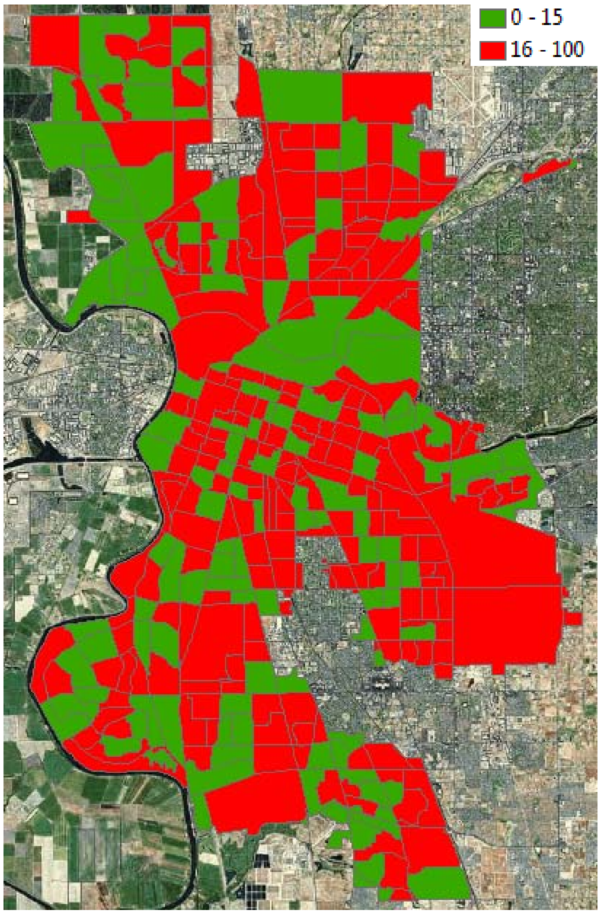
Even though the block group level data can provide more detailed information, those who use the American Community Survey must check the reliability of the data especially when using disaggregated levels. Compared to previous long form sample data (Summary File 3), ACS contains a larger margin of error (MOE) because of a lack of sample size. The Census 2000 SF3 sampled approximately one in six households at one point in 2000, while the ACS represents about one in 40 households throughout monthly surveys. As a result, ACS users must check the coefficient of variation (CV), which is a quick reference for measuring the usability of ACS estimates (ESRI 2011b). A CV can be computed directly from the MOE using the following equation:

$$\mathrm{CV} = \frac{\left(\frac{\mathrm{MOE}}{1.645}\right)}{\mathrm{ESTIMATE}} \times 100$$

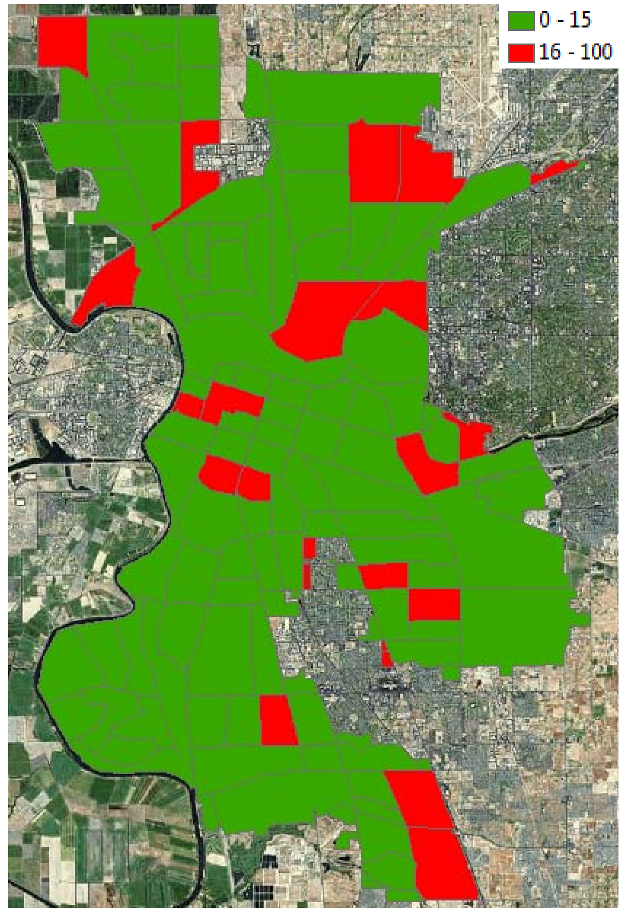
* The CV is expressed as a percentage.
*1.645 (for a 90 percent confidence interval)

A researcher can decide the amount of acceptable error in an estimate for the analysis. For example, ESRI (2011b) classified the reliability of estimates into three categories: high reliability (CV is less than or equal to 12 percent), medium reliability (CV is between 12 and 40) and low reliability (CV is larger than 40). I calculate the CV of the median household income estimates of block groups, census tracts in Sacramento and map them with two categories: usable (CV is less than or equal to 15) and needs caution (CV is larger than 15) (Figure 3.7). A large number of block groups display that users need to be cautious when using the estimates. Given this result, I decide to use track level data that shows smaller numbers of low reliability, although it is more aggregated.

Figure 3.7 Coefficient of Variation (CV) of median household income



Census Block Groups



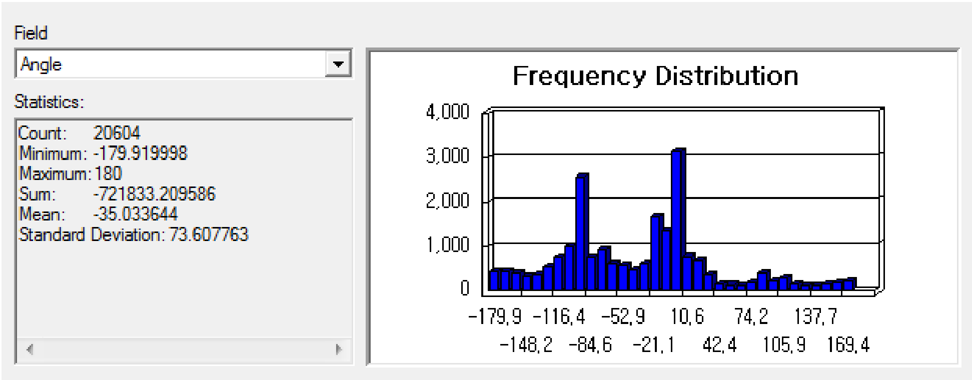
Census Tracts

*CV is Less than or equal to 15—Usable; CV is Larger than 15—Need caution.

Street Orientation

Calculating street orientation for individual parcels is one of the major analyses in this study. Using addresses of parcels from property data, I perform address geocoding in ArcGIS and map the location of each parcel along street lines. I split the lines at the vertices and calculate the angles of each split line. By performing a spatial join, angles of split lines are assigned to the points of the parcels on the street lines.

Figure 3.8 Descriptive statistics of street angles



As seen in Figure 3.8, the angles range from -180 to 180 degrees with continuous values. In order to create categorical variables for street orientation, I classify a continuous form of angles into four categories: East-West (EW), North-South (NS), Northeast-Southwest (NESW) and Northwest-Southeast (NWSE) (Table 3.3). Figure 3.9 illustrates an example of the categorization of the street orientation on the map.

Table 3.3 Categories of street orientation

Categories	Condition	Fraction
EW	(("Angle" < 22.5) AND ("Angle" > -22.5)) OR (("Angle" >157.5) AND ("Angle" <= 180)) OR (("Angle" <-157.5) AND ("Angle" >= -180))	40.1%
NS	(("Angle" < 112.5) AND ("Angle" > 67.5)) OR (("Angle" < -67.5) AND ("Angle" > -112.5))	30.5%
NESW	(("Angle" < 67.5) AND ("Angle" > 22.5)) OR (("Angle" < -112.5) AND ("Angle" > -157.5))	14.4%
NWSE	(("Angle" < 157.5) AND ("Angle" > 112.5)) OR (("Angle" < -22.5) AND ("Angle" > -67.5))	14.9%

Figure 3.9 Street orientation for individual parcels

ANGLE	STORIT
79.8	NS
-67.8	NS
-64.13	NWSE
-142	NESW
-100.55	NS
-100.43	NS
79.8	NS
165.49	EW
165.49	EW
79.8	NS
-10.86	EW
-10.86	EW
-100.55	NS
-137.82	NESW
-142	NESW
-148.57	NESW
79.8	NS
165.49	EW
165.49	EW
165.49	EW
177.14	EW
-164.62	EW
-148.57	NESW
-14.01	EW

Green Space Density

I defined "green space density" as the ratio of green space area per unit area. To calculate green space density, I use a land cover image for Sacramento obtained from the USDA Forest Service (Dr. Qingfu Xiao at UC Davis). The image is created using unsupervised classification with a moving mask of Quickbird data (2004-2006). The land cover categories are: tree (green), irrigated grass (light green), impervious surface (grey), bare soil and dry grass (brown) (Figure 3.10). I reclassify the original classification into two categories: green (the sum of tree and irrigated grass) and otherwise. To use Kernel Density, I convert each pixel into points and calculate the density of green space with a 100ft radius to show the immediate vicinity and those with 500ft radius to represent neighborly effects. As seen in Figure 3.11, green space density for a larger radius produces smoother values across the site.

Figure 3.10 Comparison between aerial photo and land cover classification

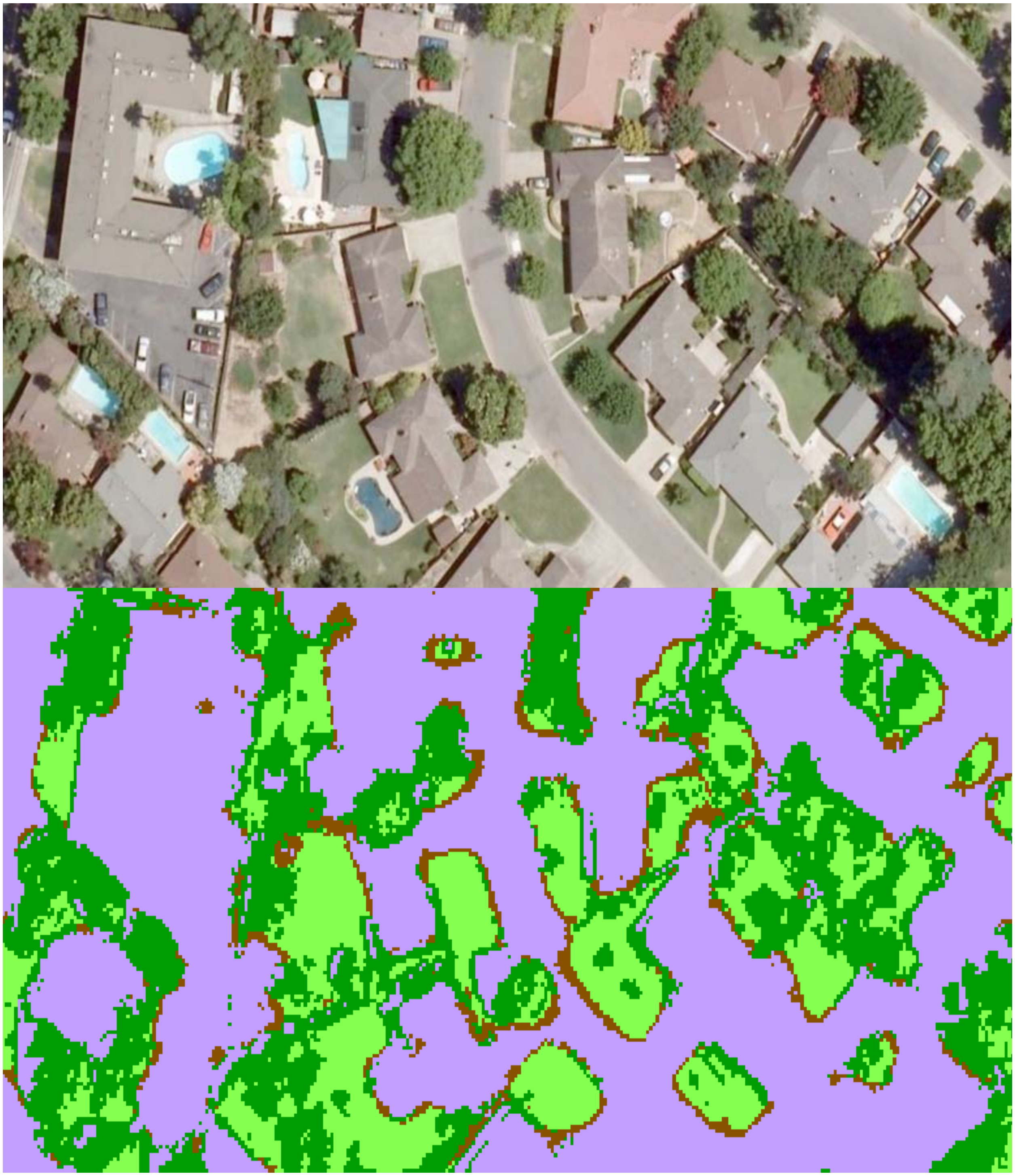
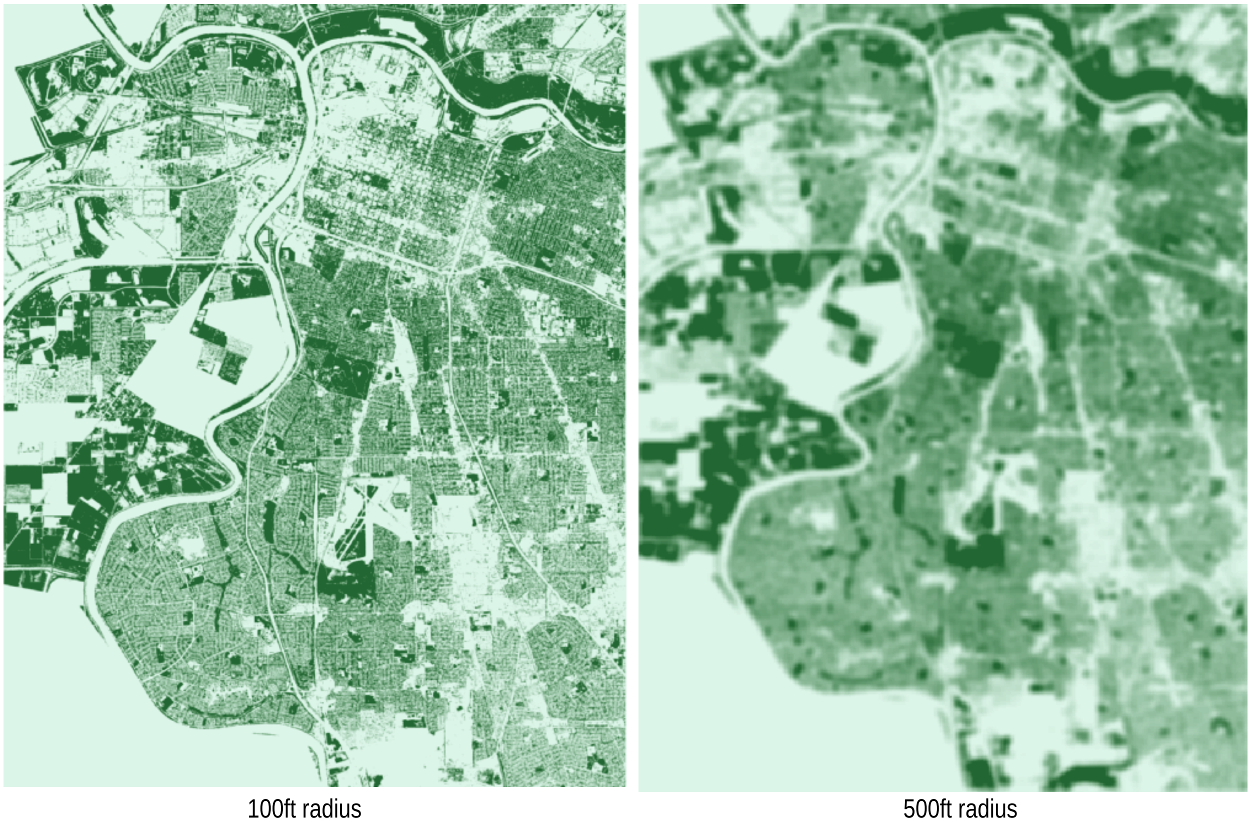


Figure 3.11 Green space density in Sacramento



Water Body Density

I define "water body density" as the ratio of both natural and artificial water-bodies area per unit area (e.g. rivers, creeks and pools). I extract water-bodies from LiDAR data exploiting the fact that there is no return pulse in water bodies due to the fact that water bodies absorb the near-infrared light that LiDAR uses. Therefore, in LiDAR point clouds, water bodies are typically detected with holes that are distinctively larger than the average spacing of point clouds. In order to distinguish water bodies from regular point spacing, I use the functions "Expand" and "Shrink" in ArcGIS (Crawford 2009). By "expanding" one meter outward, I eliminate most of the small gaps that had been generated from point spacing while larger holes still remained. In this stage, I use "Shrink" for one meter to recover the original size of large holes.

Like green space density, I classify the image into two categories: water (blank) and no value (black) (Figure 3.12). I convert each pixel into points and calculate the density of water bodies with a 100ft radius to show immediate vicinity and those with a 500ft radius to represent a neighborly effect using Kernel Density (Figure 3.13).

Figure 3.12 Extracting water bodies

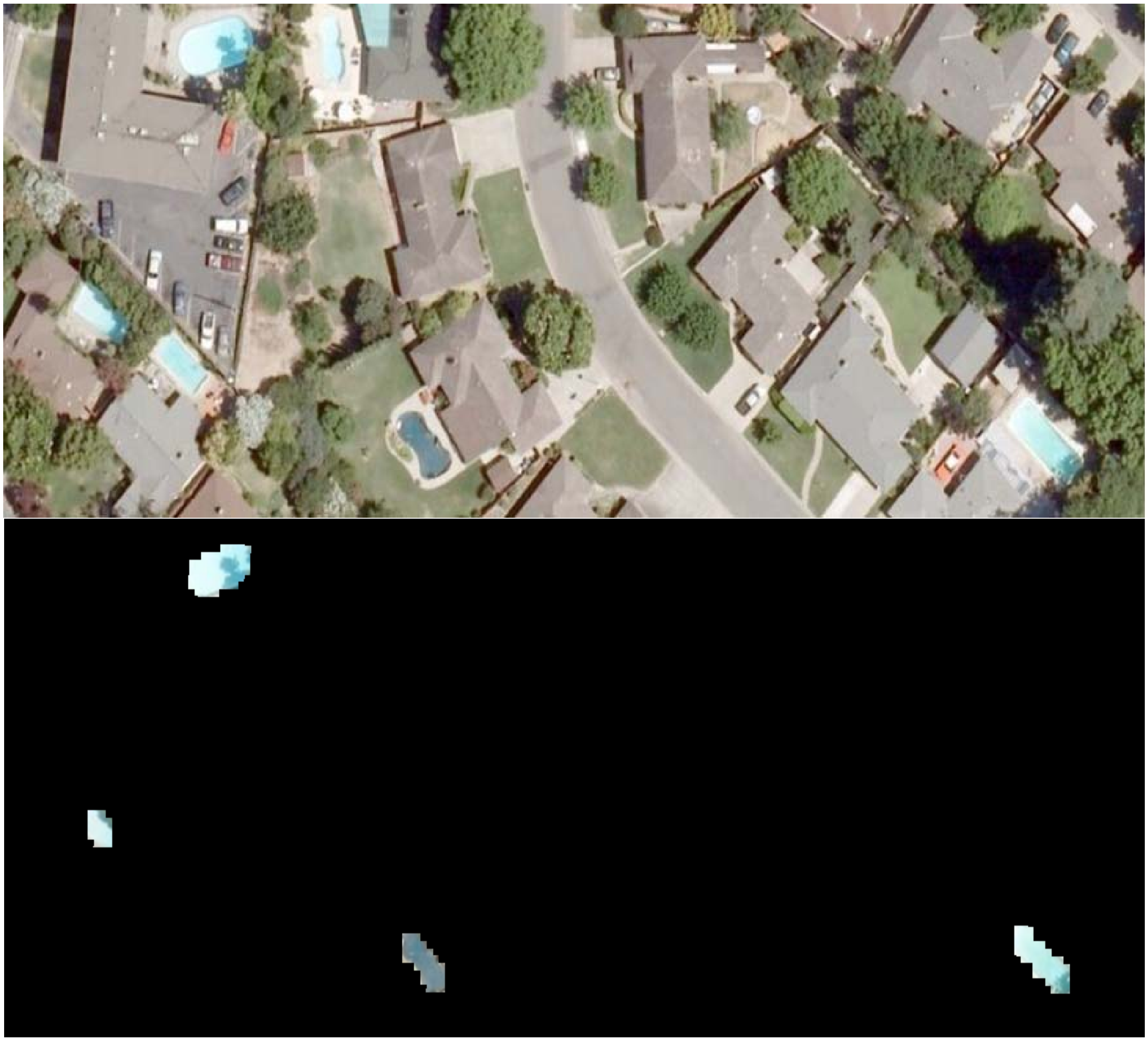
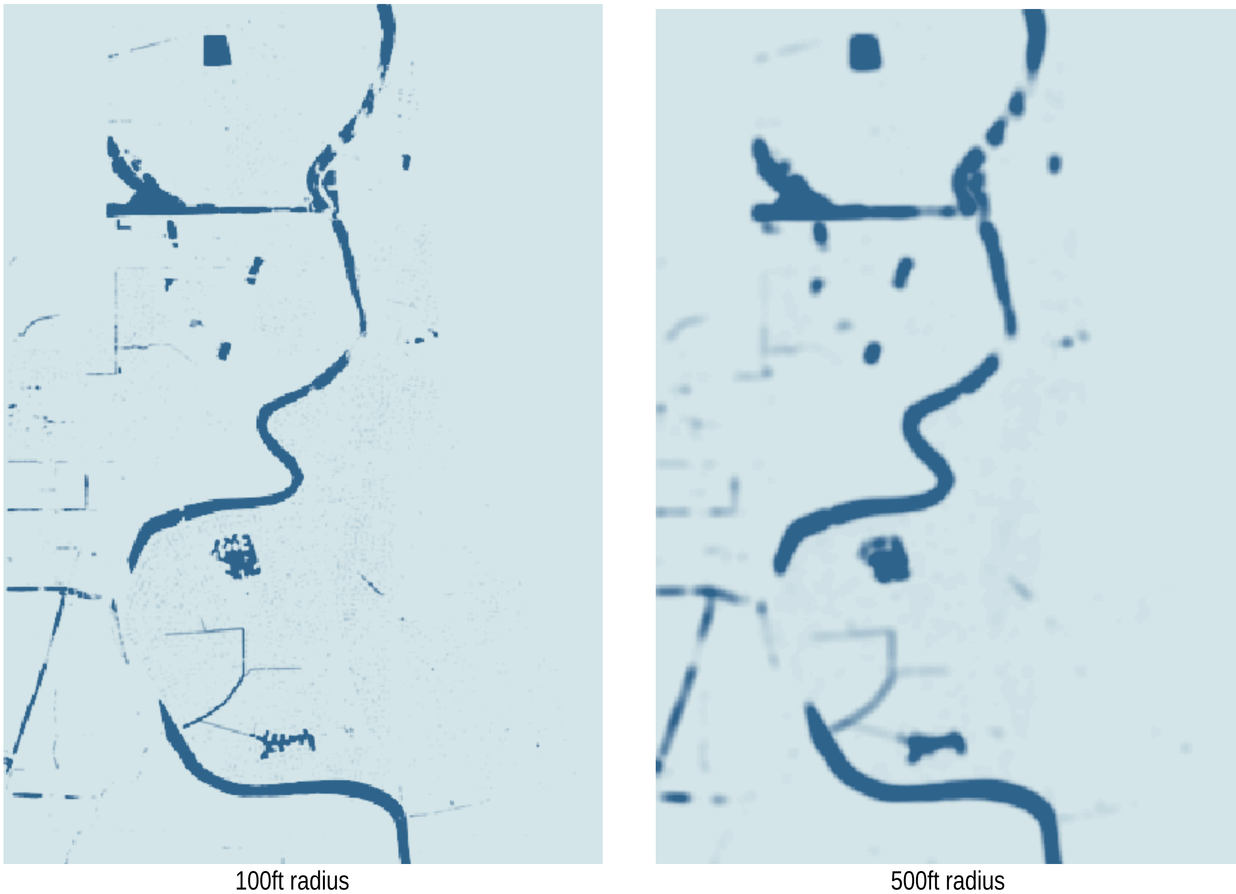


Figure 3.13 Water body density in Sacramento

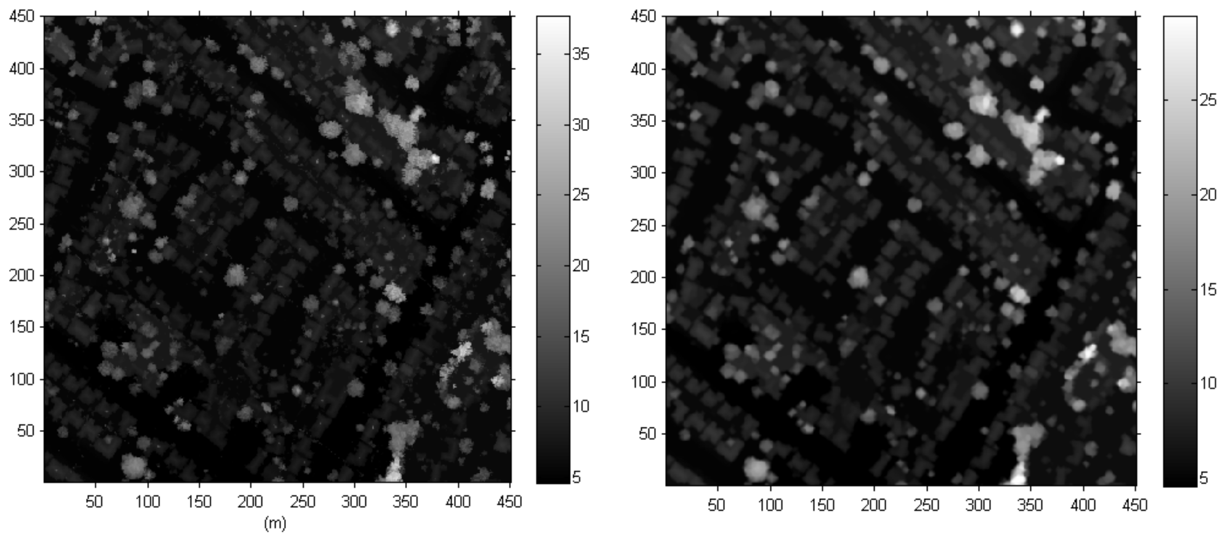


Tree Heights[1]

In addition to green space density, I include tree heights with their configuration in relation to a house. The inclusion of tree heights with their configuration is important in that it allows the research to account for more detailed effects of trees with 3D information. To measure tree heights, I detect treetops from the Digital Surface Model (DSM) derived from LiDAR points. I first smoothed the elevation value by applying the Gaussian low-pass filter to reduce the small spikes of each object in the DSM (Figure 3.14).

[1] Tree heights were measured using algorithms originally developed by Dr. Junhak Lee (Lee 2010).

Figure 3.14 Smoothing Digital Surface Model (DSM)

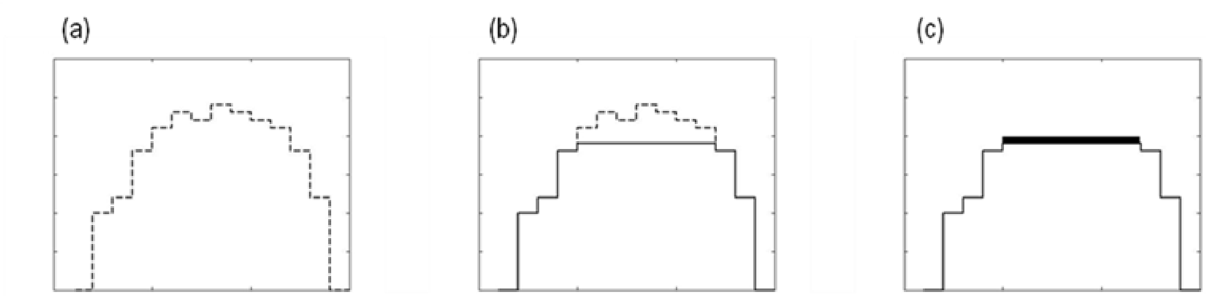


*Lighter gradation indicates higher elevation.

In order to detect treetops, I first detect blobs in the DSM using the extended-maxima transform that is known as a useful method to detect tree tops ("maximal structure") in the canopy surface model (Lee 2010). Extended-maxima transformation is the regional maxima of the H-maxima transformation that suppresses all maxima whose depth is lower than or equal to a given threshold level h (here, h = 0.5m) (Lee 2010). Figure 3.15 illustrates how the regional maxima transformation recognizes "objects" that are higher than their surroundings. The extended-maxima transformation eliminates small fluctuations of the tree canopies (b) and can detect the cap of the canopies (c). In this study, these detected blobs include caps of trees and partial roof planes of buildings (Figure 3.16).

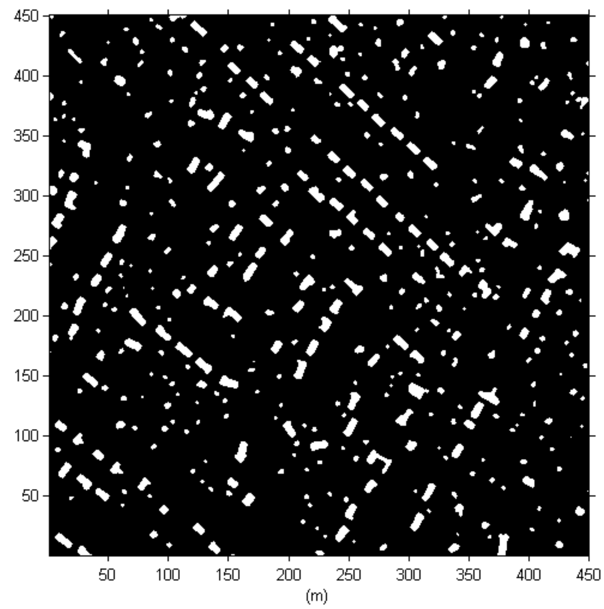
$$\mathrm{EMAX}_h(f) = \mathrm{RMAX}\left[\mathrm{HMAX}_h(f)\right]$$

Figure 3.15 Detecting tree plateaus using regional maxima transformation



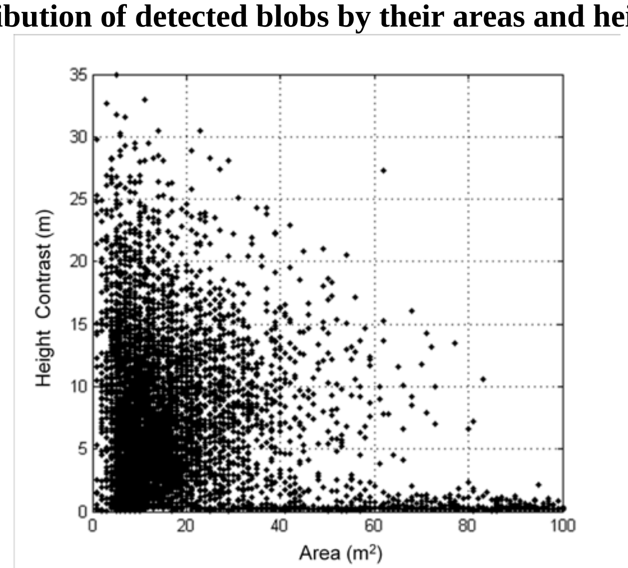
Modified from (Lee et al., In review)

Figure 3.16 Detected blobs that include plateaus of trees and buildings



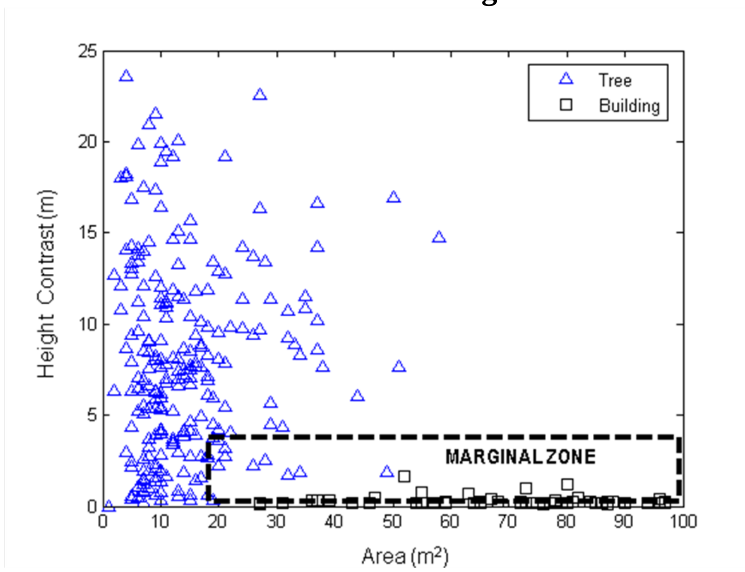
The next step is classifying detected blobs into trees and buildings. In this classification, I use two criteria: the size and the height contrasts of detected blobs. In general, the size of the detected blob from trees is smaller to that of buildings. The size of a detected blob from a big broad-leaved tree is similar to that of a small house. Height contrast is the difference between the maximum height and the minimum height. The height contrast value of trees is much greater than that of a building because LiDAR pulses can pass through sparse tree canopies. In contrast, LiDAR pulses are all reflected on roof planes, as they are solid objects. I calculate height contrasts for each grid cell. Figure 3.17 illustrates the distributions of detected blobs by their areas and height contrasts.

Figure 3.17 The Distribution of detected blobs by their areas and height contrasts



Linear discriminant analysis is used to determine the threshold of classification. Within the study area, I select a 1.8 km by 1.8 km sample site and randomly select 292 samples out of 6,182 detected blobs to check the distribution of the points. Most confusion between trees and buildings existed near the marginal area between two groups (Figure 3.18), and as a result I select 305 random points from this marginal zone where the detected blobs are in the range of 20 to 110 m^2 and the height contrast is between 0.5 and 3m.

Figure 3.18 Marginal zone between trees and buildings



In order to check the accuracy of the method, I conduct an accuracy assessment. I used 176 points for training the model and use 129 points for the accuracy assessment. Tables 3.4 to Table 3.6 present the results of the accuracy assessment and show that this method classifies trees from buildings with high accuracy. Figure 3.19 and Table 3.4 show the overall accuracy of training for the marginal area is 88.64%. Figure 3.20 and Table 3.5 show the overall accuracy of the test for the marginal area is 89.92%. Finally, Figure 3.21 and Table 3.6 present the overall accuracy of the test for the entire tile (1.8 km by 1.8 km) is 99.31%: only one building was falsely classified as a tree. Figure 3.22 illustrates an example of treetop detection with DSM.

Figure 3.19 Distribution of buildings and trees (Training at the marginal zone)

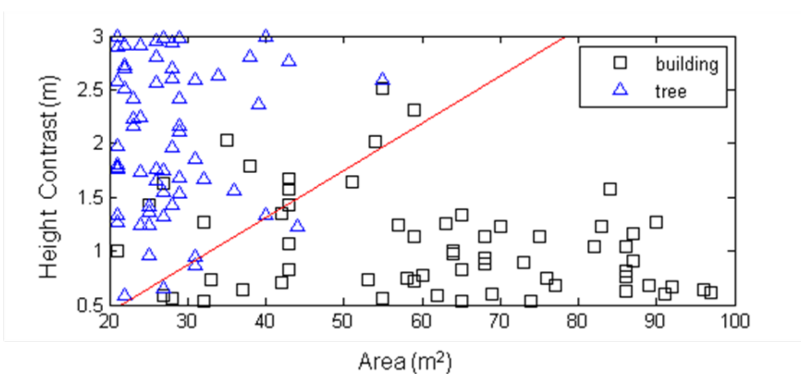


Table 3.4 Confusion matrix (Training at the marginal zone)

		Reference		
		Buildings	*Trees*	*Total*
Classification	*Buildings*	76	4	80
	Trees	16	80	96
	Total	92	84	176

Overall accuracy = 88.64%

Figure 3.20 Distribution of buildings and trees (Testing at the marginal zone)

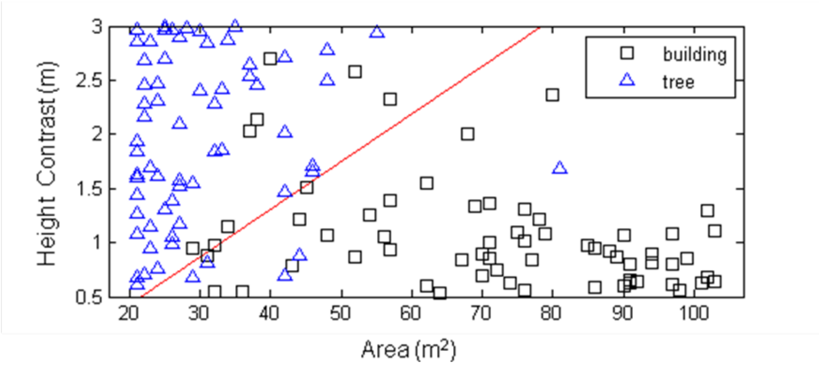


Table 3.5 Confusion matrix (Testing at the marginal zone)

		Reference		
		Buildings	*Trees*	*Total*
Classification	*Buildings*	56	5	61
	Trees	8	60	68
	Total	64	65	129

Overall accuracy = 89.92%

Figure 3.21 Distribution of buildings and trees (Testing at the entire tile)

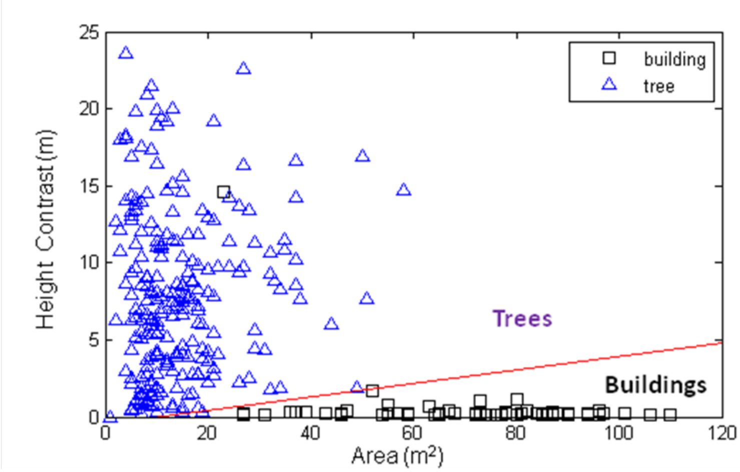
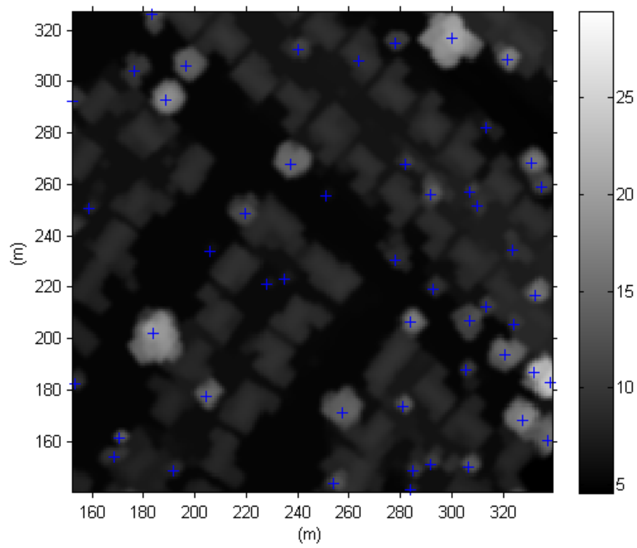


Table 3.6 Confusion matrix (Testing at the entire tile)

		Reference		
		Building	*Tree*	*Total*
Classification	*Building*	60	1	61
	Tree	1	230	231
	Total	61	231	292

Overall accuracy = 99.32%

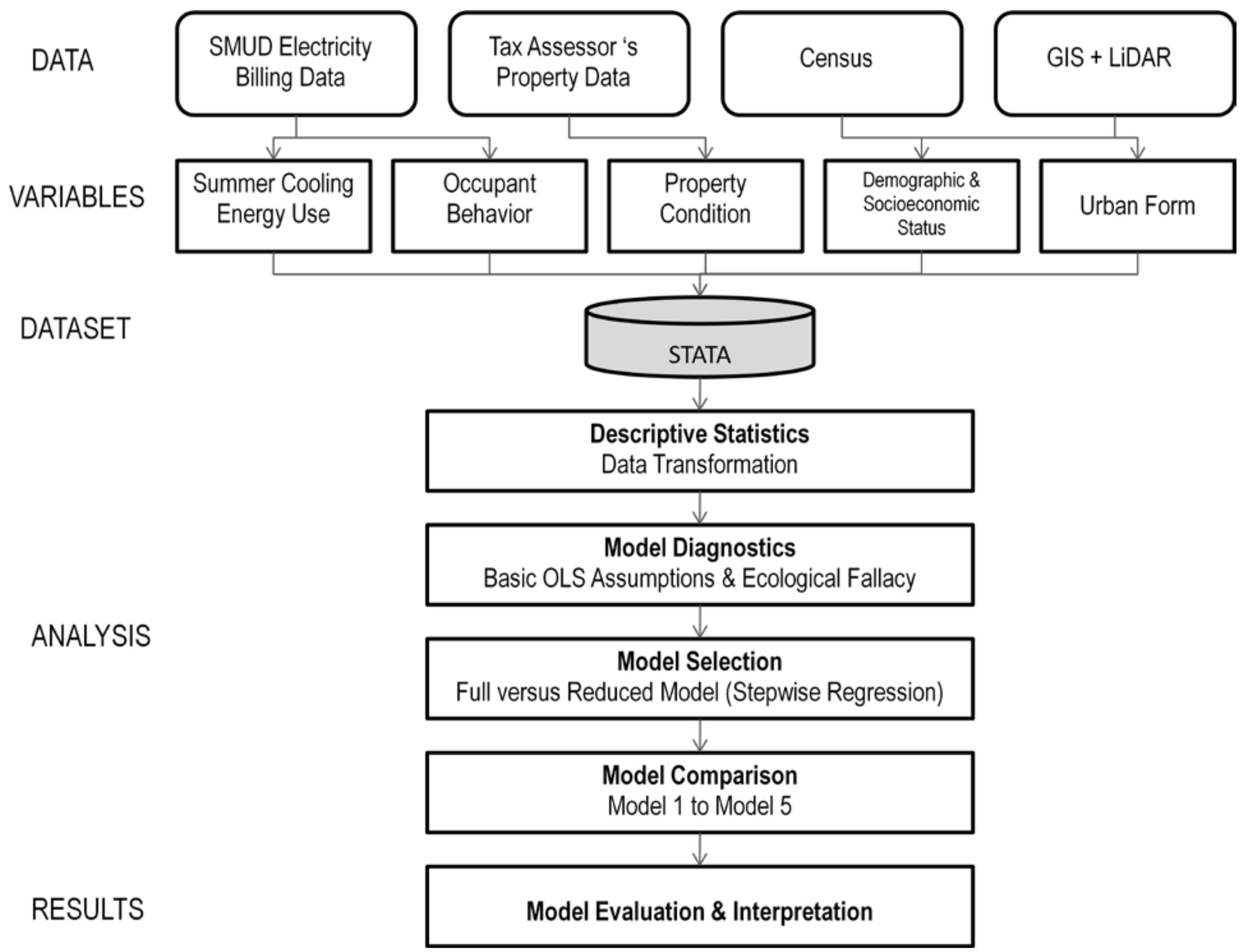
Figure 3.22 Treetops detected on DSM



3.5 Statistical Analyses

In this section, I review the entire process of statistical analyses that I employ in this study. As the illustration of the modeling procedure shows (Figure 3.23), the entire process of analyses includes data collection, variable extraction, building a statistical dataset in Stata, statistical analyses and result interpretation. In the statistical analyses, I first present descriptive statistics to characterize the dataset and transform some continuous variables to ensure linearity and achieve normality. In the second step I check model assumptions. In addition to checking the basic assumptions of the Ordinary Least Square (OLS) model, I check a potential ecological fallacy that may stem from an inference using multi-level data (i.e. parcel versus census blocks and tracts). In a third step, I explore predictor selection in order to build efficient and non-biased models. Using stepwise regression, I compute a reduced model and compare model indicators of the full model with those of the reduced model to check whether I detect significant improvements. After finalizing the predictors to be included in the model, I build five regression models by sequentially adding five different groups of predictors (occupant behavior, demographic & socioeconomic status, property condition, urban from I and urban form II). I compare them by performing Wald tests and check whether each group of predictors has a significant impact after controlling for other groups of predictors. Finally, I present and interpret the results. I explain the details of each step while presenting the results in the following section.

Figure 3.23 Modeling procedure



3.6 Results

3.6.1 Descriptive Statistics

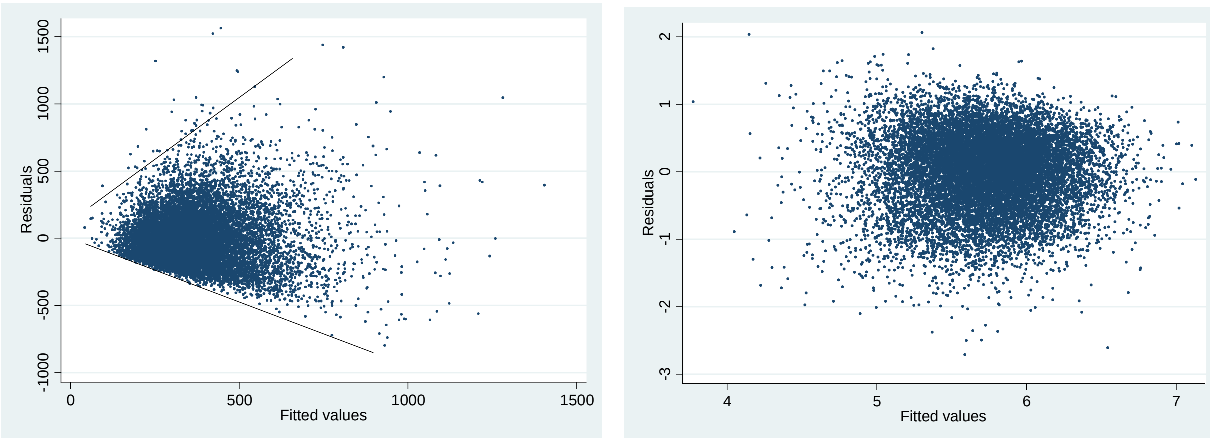
Table 3.7 illustrates the descriptive statistics for the continuous variables. After screening parcels based on data quality, 13,709 cases in our study area are included in the analysis. The average monthly summer cooling electricity use (the response variable) has a mean of 375.05kWh with a range of 12.7kWh (min) and 2327.8 kWh (max).

Table 3.7 Descriptive statistics of continuous variables

Variable	N	Mean	Std. Dev.	Min	Max
Response Variable					
Average Monthly Summer Cooling Electricity Use (kWh)	13709	375.054	239.856	12.667	2327.833
Explanatory Variables					
Baseline Electricity Use (kWh)	13709	682.023	339.364	42.75	3471
Percentage of White (0~1)	13709	.381	.194	0	.97
Racial Diversity Index (0~1)	13709	.648	.116	0	.79
Percentage of Bachelor's degree or higher degree (0~1)	13709	.395	.161	.08	.75
Percentage of Over 18 (0~1)	13709	.792	.093	0	1
Net Assessed Property Value ($)	13709	213496	145209.6	9284	1300000
Annual Household Median Income ($)	13709	65360.6	17516.81	28689	96540
Total Floor Area (sq.ft)	13709	1866.133	623.591	710	6409
Garage Area (sq.ft)	13709	477.998	189.129	0	3593
Population Density per Acre	13709	9.889	4.116	.78	29.53
Dwelling Unit Density per Acre	13709	4.048	1.374	.93	13.73
Green Space Density in 100ft radius	13709	.011	.004	0	.027
Green Space Density in 500ft radius	13709	.011	.003	.001	.022
Water Bodies Density in 100ft radius	13709	.0001	.0003	0	.004
Water Bodies Density in 500ft radius	13709	.0003	.001	0	.018
Sum of Tree Heights in the East of Property within 30ft radius	13709	.906	3.45	0	36.693
Sum of Tree Heights in the South of Property within 30ft radius	13709	1.623	4.595	0	62.481
Sum of Tree Heights in the West of Property within 30ft radius	13709	2.050	5.376	0	67.031
Sum of Tree Heights in the North of Property within 30ft radius	13709	2.353	5.737	0	67.236
Sum of Tree Heights in the East of Property within 60ft radius	13709	3.716	6.587	0	70.739
Sum of Tree Heights in the South of Property within 60ft radius	13709	7.619	9.629	0	67.532
Sum of Tree Heights in the West of Property within 60ft radius	13709	7.662	9.562	0	90.967
Sum of Tree Heights in the North of Property within 60ft radius	13709	7.845	9.670	0	88.328

In order to moderate heteroscedasticity and ensure a linear relationship between predictors and the response variable, I transform some continuous variables into natural log form. Figure 3.24 shows how the assumption of a constant variance of the residuals is improved through data transformation. Figure 3.24 (a) demonstrates serious heteroscedasticity in its scatter plot of residuals versus fitted values. After the transformation the amount of scatter around the horizontal line appears to be constant as seen in Figure 3.24 (b).

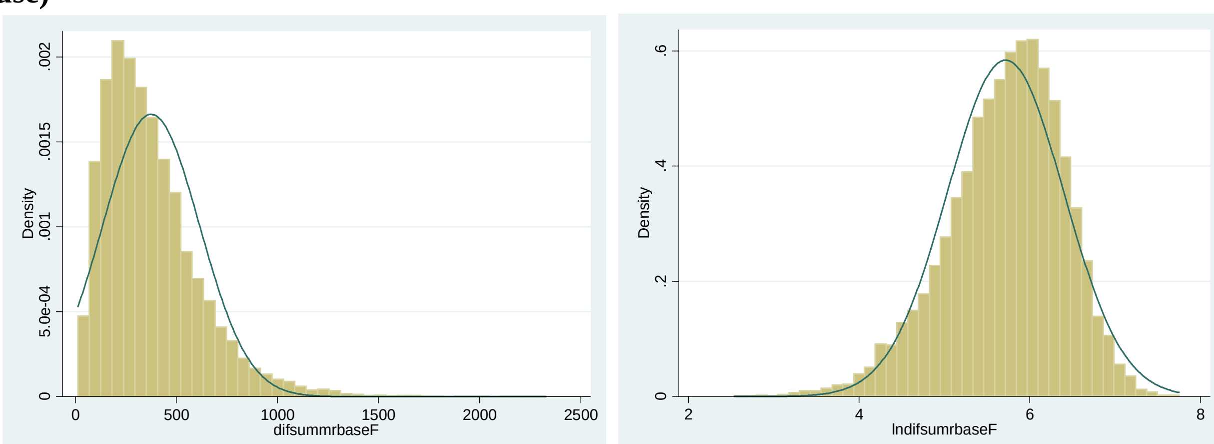
Figure 3.24 Moderating heteroschedasticity through log-log transformation



(a) Before Transformation (b) After Transformation

Furthermore, I examine the normality of continuous variables. Some continuous variables show skewed distributions. For example, Figure 3.25 (a) demonstrates that a distribution of summer cooling electricity use (the response variable) is severely skewed. By converting it to log form, the normality of the response variable has been improved (Figure 3.25 (b)). Using the same method, I also transform other continuous predictors, which contribute to a violation of assumptions, into natural log form.

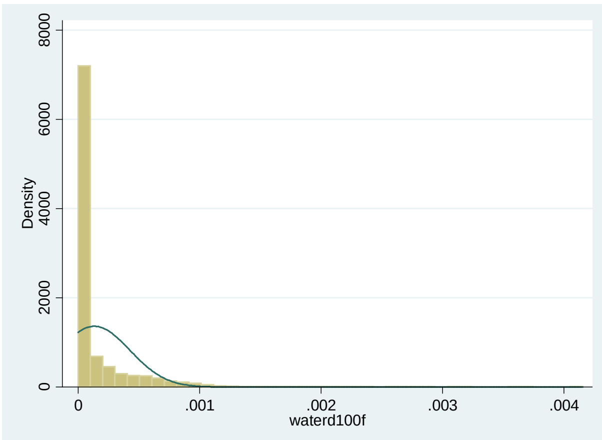
Figure 3.25 Distribution of response variable (Average monthly summer cooling electricity use)



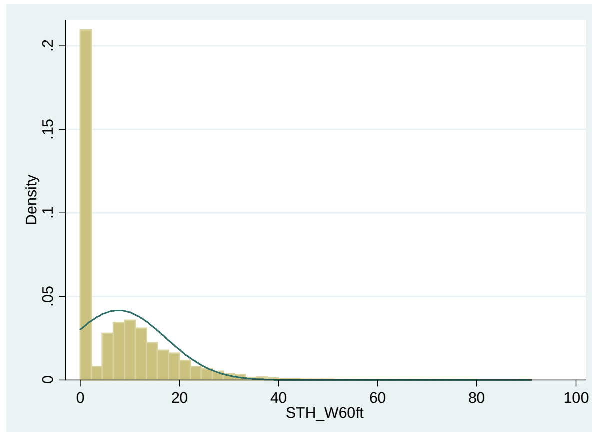
(a) Before Transformation (b) After Transformation (Log)

Although I moderate a skewed distribution through transformation, it is difficult to transform some variables such as the water body density and the sum of tree heights on each configuration because of their unique data distribution. Each of these variables contains a high frequency of 0 in their distribution (Figure 3.26). Although converting these variables into log form can possibly improve normality, log transformation of data with a high frequency of 0 results in a large number of missing values in a dataset. In other words, the trade-off from improving normality is a significant loss of cases. Due to this limitation, I do not perform log transformation on those variables but used “robust” models as an alternative to maintain study cases. Compared to standard errors from traditional models, “robust” standard errors from robust regression do not heavily rely on typical OLS assumptions and are robust to the violation of homoscedasticity and to the distributional assumptions (Rabe-Hesketh and Skrondal 2008).

Figure 3.26 Examples of distribution of predictors that show high frequency in zero



Water body density with 100ft radius



Sum of Tree Heights in the west of a house within 60ft radius

Table 3.8 shows frequency and the percentage of each categorical variable. In this dataset, the dominant housing type is single family housing (96%) built in subdivisions (90%). About half of the houses (56%) contain six to seven rooms (including both bath and bedrooms), 27% of the homes have eight rooms or more; only 16% of the houses have five rooms or less. 77% of the housing is single story homes and the rest (23%) is two story homes. 19% of the parcels contain pools and three fourths (75%) are occupied by homeowners. As for roof types, wood shake/ shingle are dominant (74%). The categories of street orientation are relatively well balanced: East-West (36%), North-South (30%), Northwest-Southeast (18%) and Northeast-Southwest (16%).

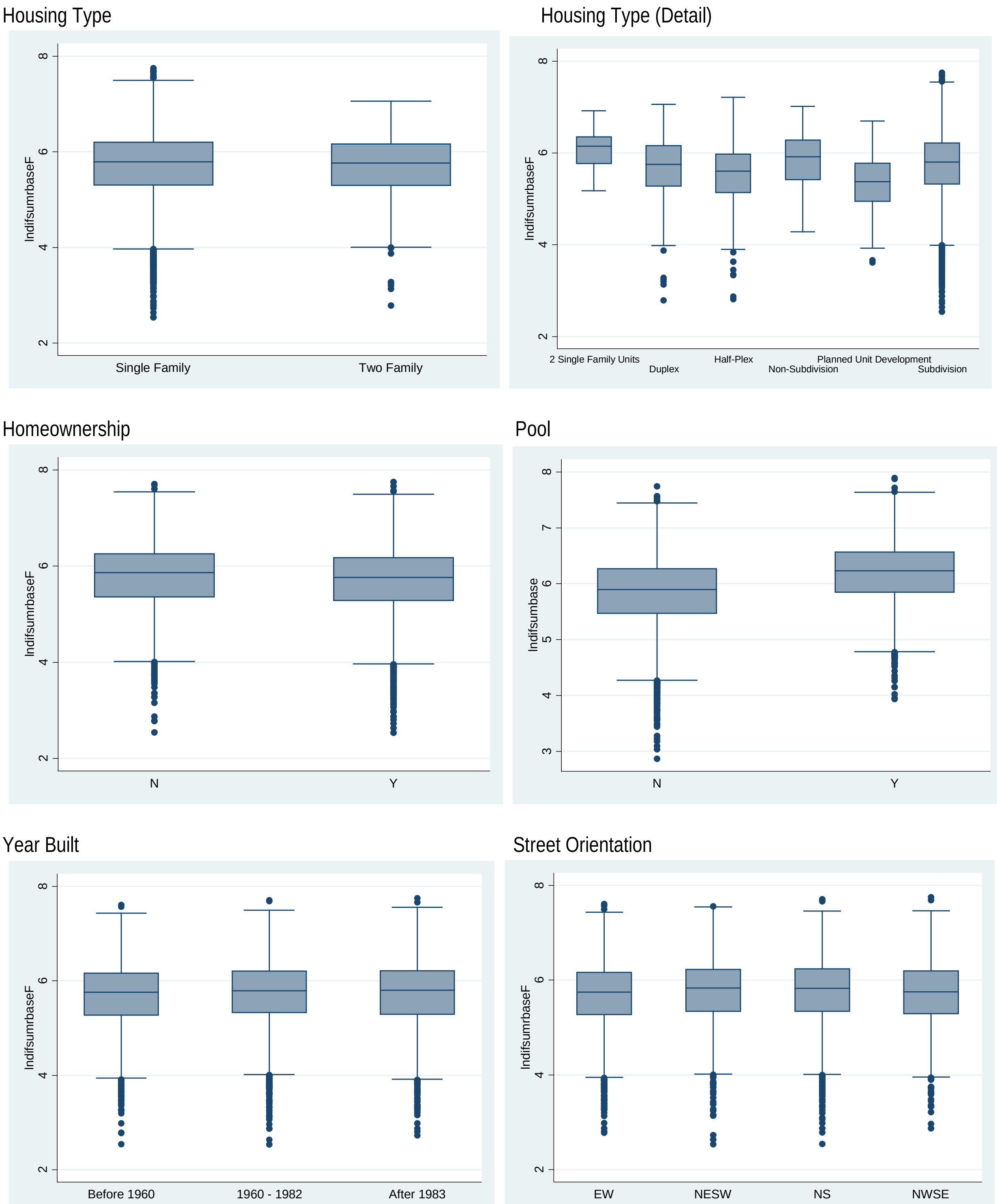
Figure 3.27 demonstrates the box plots of summer cooling electricity use (converted to natural log form) by the dummies for each explanatory variable. Some of the comparisons of the dummies are worth mentioning. As expected, the estimated mean of the cooling electricity use consumed by two families who live in a duplex is lower than that consumed by two families who live in two separate single family units of a parcel. The estimated mean of the cooling electricity use consumed by a single family who lives in a half-plex or planned unit development appears to be lower than that consumed by a single family who lives in a subdivision. The estimated mean of the cooling electricity use consumed by homeowners appears to be lower than that which has been consumed by the tenants. The estimated mean of the summer cooling electricity use in a parcel with a pool appears to be higher than that of a parcel without a pool. The difference in the estimated means of the cooling energy use among dummies for the year built and for the street orientation appears to be small before controlling for other variables.

Table 3.8 Frequency chart for categorical variables

Variable	Counts	Percentage
Year Built		
Before 1960	3,014	21.99
1960 – 1983*	6,504	47.44
After 1983	4,191	30.57
Housing Type		
Single Family*	13,201	96.29
Two Family	508	3.71
Housing Type (Detail)		
Two SF House Unit	17	0.12
Duplex	491	3.58
Half-plex	578	4.22
Non-Subdivision	18	0.13
Planned Unit Development	229	1.67
Subdivision*	12,376	90.28
Number of Stories		
1*	10,510	76.66
2	3,199	23.34
Number of Rooms		
3–5	2,261	16.49
6–7*	7,697	56.15
8 or more	3,751	27.36
Pool		
No*	11,169	81.47
Yes	2,540	18.53
Home Ownership		
No*	3,401	24.81
Yes	10,308	75.19
Rooftype		
1:Wood*	1,475	10.76
2:Wood Shake/ Shingles	10,173	74.21
3:Composition Shingle	2,061	15.30
Street Orientation		
East-West*	4,946	36.08
Northeast-Southwest	2,239	16.33
North-South	4,115	30.02
Northwest-Southeast	2,409	17.57
Total	13,709	

*is used as reference variable in the category.

Figure 3.27 Boxplot of summer cooling electricity use by the dummies for explanatory variables



3.6.2 Regression Analysis 1: Model Diagnostics

I present the results of model diagnostics in Appendix A. Overall, the basic assumptions--linearity of continuous predictors, normality of residuals and constant variance of residuals appear not to be severely violated. However, the non-normality of some continuous variables (i.e. water body density and the sum of tree heights by configuration) still remains. Thus, I use a "robust" model in order to obtain robust standard errors. Robust standard errors are robust to heteroskedaticity and to other violations of the distributional assumptions (Rabe-Hesketh and Skrondal 2008).

In addition to checking OLS assumptions, I examine a potential ecological fallacy in the model. Ecological fallacy occurs when researchers infer phenomena in disaggregated levels using aggregate data and models. The current model includes hierarchical datasets; most demographic and socioeconomic variables are derived from the upper -level (i.e. census block and track) while most variables including the response variable are based on the lower-level (i.e. parcels). Shared attributes in the upper level may contribute to group-level confounding, which can be responsible for the ecological fallacy (Rabe-Hesketh and Skrondal 2008). This erroneous inference can violate assumptions of typical OLS regression—individual cases are independent.

Hierarchical Linear Modeling (HLM) can be used to account for this multi-level data. While OLS models assume one error term (e) defined as a distance between observed values and predicted values, HLM has two error terms – the level-1 residual (ϵ_{ij}), which indicates a deviation of Y_{ij} from its true cluster mean and the level-2 residual (ζ_j), which indicates a deviation of a true cluster mean from the overall mean. These two error terms are referred to as "random effect"(Rabe-Hesketh and Skrondal 2008). In this regard, it is imperative to check whether OLS regression could be appropriate for our model or whether HLM should be used.

$$y_{ij} = \beta + \zeta_j + \epsilon_{ij}, \qquad \epsilon_{ij} | \zeta_j \sim N(0, \theta) \qquad \zeta \sim N(0, \psi)$$

The general guideline of checking the need for HLM is computing "intraclass correlation (ICC)". High ICC values (generally higher than .05) with statistically significant probability levels indicates the need for HLM by demonstrating that lower level units tend to share upper level attributes (Rabe-Hesketh and Skrondal 2008). I perform two variance-component models (also called intercept-only models) that compute ICC (1) between census blocks and (2) between census tracts.

Table 3.9 shows the results of the variance-component models. ICC (ρ) between the census blocks is only 0.04, which is lower than 0.05. ICC between the census tracts is even lower – 0.018. These results indicate that only 4% and 1.8% of the variation in the summer cooling energy use is accounted for between group variation among census blocks and among census tracts. Therefore, these results justify the use of OLS regression.

Table 3.9 Checking intraclass correlation among census blocks and among census tracts

	N	Intraclass Correlation (ICC)
Census Blocks	894	0.0395
Census Tracts	23	0.0182

3.6.3 Regression Analysis 2: Model Building

The next step that researchers should take is exploring a model that best accounts for the phenomena. In this stage, researchers must consider the trade-off of under specification by failing to include all of the relevant variables versus over specification by adding irrelevant variables (Chatterjee and Hadi 2006). Initially I built a comprehensive model that includes all of the 38 explanatory variables that were created based on theory. However, including all of the variables does not always produce the "best" model that efficiently explains the phenomena. The inclusion of irrelevant variables often results in reducing the efficiency of the model (Chatterjee and Hadi 2006).

In order to build an efficient but unbiased model, I first test a stepwise regression and removed variables that are less relevant variables in the model. I use a combination of confirmatory and exploratory approaches that forced some of the explanatory variables of our interests into the model. As for explanatory variables with more than two categories, the corresponding dummy variables are considered as a group and included all together in the model. Using backward elimination, I eliminate variables if their probability was less than 0.4. As a result, lot size, green space density (500ft radius), median household income, dwelling unit density, two story home, the percentage of people over 18 and the percentage of white and racial diversity index are removed in the reduced model.

When comparing the results between the full and reduced models (Table 3.10), the model indicators show that the efficiency of the new reduced model is not significantly different. After removing eight variables, R^2 of the reduced model is as constant 0.3106, which is slightly lower than that of the full model (.3108). The reduced model shows lower collinearity than the full model. In the reduced model, a mean of Variance Inflation Coefficient (VIF, which indicates the level of collinearity) decreased from 1.86 to 1.57. The largest VIFs were "percentage of bachelor's degree" (4.52) in the full model and "total floor area" (3.75) in the reduced model. Both VIFs were far less than 10 (the threshold for warning collinearity), indicating that there is no serious collinearity in both models.

The general rule of model specification is that it is better to include insignificant variables if theory suggests that variables belong in the equation and that the sample size is large (N >1000) (Chatterjee and Hadi 2006). Since there is not much significant difference between full and reduced models, I decide to keep most of the removed variables that are supported by theory. In this regard, I include green space density (500ft radius), dwelling unit density, two story home and the percentage of white and racial diversity index in the model. I exclude median household income, which is highly statistically insignificant in the full model, assuming that the census track level data does not properly represent the difference of median household income among individual homes. I assume that the economic status of the occupants can also be represented by other variables such as net assessed property value and homeownership.

Table 3.10 Multiple linear regression results (Full model versus reduced model)

Variables	Full Model		Reduced Model	
	Coefficient	P-value	Coefficient	P-value
Ln(Baseline Electricity Use)	.726754	<0.001	.7258241	<0.001
Percentage of White	-.04058	0.360		
Racial Diversity Index	-.0655432	0.274		
Percentage of Bachelor's degree or higher degree	-.2035245	0.002	-.1826232	<0.001
Percentage of Over 18	.0495278	0.473		
Annual Household Median Income	1.92e-07	0.705		
Ln(Net Assessed Property Value)	.0153715	0.108	.0149306	0.114
Homeownership	-.0948606	<0.001	-.0946344	<0.001
Built Before 1960	.0895576	<0.001	.0899206	<0.001
Built After 1983	-.0611309	<0.001	-.0641294	<0.001
Two story house	-.0102559	0.509		
Ln(Total Floor Area)	.193942	<0.001	.1899231	<0.001
Three to Five Rooms	-.0011974	0.941	-.0011569	0.943
Eight Rooms or More	.0262099	0.092	.0248282	0.100
Garage Area	-.0000281	0.379	-.0000297	0.348
Lot Area	-3.63e-07	0.863		
Two Single Family Unit	.199083	0.004	.1946587	0.004
Duplex	-.0289042	0.364	-.026914	0.391
Halfplex	-.0862118	0.002	-.0864157	0.002
Nonsubdivision	.0679241	0.542	.0645836	0.563
Planned Unit Development	-.2433818	<0.001	-.2463761	<0.001
Pool	-.0398921	0.016	-.0409572	0.013
Roof with Wood Shake/Shingle	.0037262	0.844	.0034557	0.852
Roof with Composition Shingle	.0524172	0.008	.0518849	0.008
Ln(Population Density per Acre)	-.0374283	0.017	-.0312362	0.010
Ln(Dwelling Unit Density per Acre)	.014113	0.511		
Northeast-Southwest Street	.0530981	<0.001	.0526761	<0.001
North-South Street	.0430389	0.001	.0415949	0.001
Northwest-Southeast Street	.0483602	0.001	.047957	0.001
Green Space Density in 100ft radius	-6.932933	<0.001	-7.157496	<0.001
Green Space Density in 500ft radius	.5133007	0.858		
Water Bodies Density in 100ft radius	-35.71507	0.138	-34.68398	0.147
Water Bodies Density in 500ft radius	8.436262	0.147	8.186297	0.138
Sum of Tree Heights in the East of Property within 30ft radius	.0021602	0.172	.0021427	0.176
Sum of Tree Heights in the South of Property within 30ft radius	.001293	0.282	.0012682	0.291
Sum of Tree Heights in the West of Property within 30ft radius	.0017536	0.112	.001752	0.112
Sum of Tree Heights in the North of Property within 30ft radius	-.0013753	0.187	-.0013892	0.181
Sum of Tree Heights in the East of Property within 60ft radius	-.0017521	0.045	-.0017839	0.041
Sum of Tree Heights in the South of Property within 60ft radius	-.0013643	0.023	-.0013692	0.022
Sum of Tree Heights in the West of Property within 60ft radius	-.0024277	<0.001	-.0024381	<0.001
Sum of Tree Heights in the North of Property within 60ft radius	-.0004749	0.466	-.0004875	0.453
Constant	-.2614001	0.313	-.2234381	0.322
R^2	0.3108		0.3107	
F-value	126.64		157.03	
N	13709		13709	
Maximum VIF	4.52		3.75	
Average VIF	1.86		1.57	

3.6.4 Regression Analysis 3: Model Comparison

I evaluate five models in order to sequentially examine the effects of occupant behavior, demographic & socioeconomic status, property condition, community layout (urban form I), land cover and vegetation (urban form II) on summer cooling electricity use. Model 1 includes the baseline energy use in fall and spring that represents the occupant behavior from energy use and the energy efficiency of non-cooling related electric devices on the property. Model 2 adds a group of variables that represents demographic & socioeconomic characteristics – race, education, assessed value of the property and homeownership. Model 3 adds a group of variables that represent property characteristics— year built, the number of rooms and stories, housing type, roof type and the existence of a pool. Model 4 and Model 5 add urban form characteristics. Model 4 includes a group of variables that represent community layout: population density, dwelling unit density and street orientation. Model 5 includes land cover and neighboring tree settings. Land cover is represented by green space density and water body density with a 100ft radius and a 500ft radius that accounts for the immediate vicinity and for neighborly effects. Neighboring tree settings are represented by the sum of the tree heights for four configurations (North, South, East and West) with a 30ft radius and a 60ft radius.

Table 3.11 presents the results of each model. The overall model fits all five models, that are statistically significant (F= 126.64 ~4565.16, $p<.001$). As more variables are added, the R^2 of the models increase. The final model (model 5) shows that the variables included in the model explain 31.1% of the variation in summer cooling electricity use. I focus on the results of model 5 for the purpose of interpretation.

Table 3.11 The Comparison of Multiple Linear Regression Results (Model 1 ~ Model 5)

Predictors	Coefficient				
	Model 1	Model 2	Model 3	Model 4	Model 5
Occupant Behavior (& System Efficiency) Characteristics					
Ln(Baseline Electricity Use)	.738***	.734***	.719***	.720***	.727***
Demographic & Socioeconomic Characterisitcs					
Percentage of White		-.061†	-.090**	-.103**	-.030
Racial Diversity Index		-.254***	-.079	-.100†	-.053
Percentage of Bachelor's degree or higher degree		-.175***	-.186***	-.223***	-.181***
Ln(Net Assessed Property Value)		.026**	.015	.016†	.015
Homeownership		-.079***	-.095***	-.095***	-.095***
Property Condition Characteristics					
Built Before 1960			.077***	.083***	.088***
Built After 1983			-.053***	-.044**	-.062***
Two story house			-.023	-.021	-.011
Ln(Total Floor Area)			.234***	.223***	.194***
Three to Five Rooms			.002	.002	-.001
Eight Rooms or More			.025	.025	.027†
Garage Area			-.000	-.000	-.000
Two Single Family Unit			.203**	.201**	.196**
Duplex			-.026	-.025	-.029
Halfplex			-.062*	-.065*	-.084**
Nonsubdivision			.069	.065	.065
Planned Unit Development			-.205***	-.221***	-.241***
Pool			-.043**	-.044**	-.040*
Roof with Wood Shake/Shingle			.0115	.009	.004
Roof with Composition Shingle			.0477*	.051*	.051**
Urban Form I (Community Layout) Characteristics					
Ln(Population Density per Acre)				-.034*	-.039*
Ln(Dwelling Unit Density per Acre)				.012	.014
Northeast-Southwest Street				.050**	.053***
North-South Street				.036**	.042**
Northwest-Southeast Street				.046**	.048**
Urban Form II (Land Cover & Neighboring Vegetation) Characteristics					
Green Space Density in 100ft radius					-7.006***
Green Space Density in 500ft radius					.353
Water Bodies Density in 100ft radius					-36.000
Water Bodies Density in 500ft radius					7.715
Sum of Tree Heights in the East of Property within 30ft					.002
Sum of Tree Heights in the South of Property within 30ft					.001
Sum of Tree Heights in the West of Property within 30ft					.002
Sum of Tree Heights in the North of Property within 30ft					-.001
Sum of Tree Heights in the East of Property within 60ft					-.002*
Sum of Tree Heights in the South of Property within 60ft					-.001*
Sum of Tree Heights in the West of Property within 60ft					-.002***
Sum of Tree Heights in the North of Property within 60ft					-.000
Constant	.9887683	1.022397	-.5781356	-.4518729	-.221
R^2	0.289	0.292	0.306	0.307	0.311
F-value	4565.16	781.38	241.40	196.78	126.64
N	13709	13709	13709	13709	13709

*p<0.05; **p<0.01; ***p<0.001

Among five groups of variables, the first factor—occupant behavior appears to have a dominant impact on summer cooling energy use. Model 1 shows that occupant behavior solely accounts for 28.7% of variance in summer cooling electricity use. Model 5 shows that after controlling for other variables, occupant behavior is statistically significant. Parcels that consume 10% more electricity for everyday life tend to consume 7.3% more electricity for cooling in summer. As seen, standardized regression coefficients (beta) and the independent effect of the occupant's energy use behavior on summer cooling electricity use is exclusively greater than those of other predictors (Table 3.12).

Among demographic & socioeconomic factors, education attainment levels and homeownership appear to be statistically significant predictors of summer cooling energy use. When controlling for other variables, the higher the percentage of bachelors or higher degrees in a census track, the more likely the individual parcels in the census track are to consume less electricity for air conditioning ($t= -3.80$, $p<.001$). In addition, homeowners tend to use less summer cooling electricity than those who do not own homes (-7.71, $p<.001$). The effects of race composition and net assessed value of property show significant effects in partial models but are not statistically significant in the final model (model 5).

As for property condition characteristics: year built, existence of a pool, certain housing size variables, housing type and roof type show statistically significant associations with summer cooling electricity use. The effect of year built composition is significant at the 0.001 level. Compared to a house built in 1960s to early 1980s, one built before 1960 tends to use more summer cooling electricity ($t=5.71$, $p<.001$) after adjusting for other variables. On the other hand, a house built after 1983 is likely to use less summer cooling electricity ($t=-4.10$, $p<.001$). Certain variables of housing size and housing types are also significant predictors of the response variable. When controlling for other predictors, a parcel with a 10% larger square footage of structure tends to increase 1.9% of the summer cooling electricity use ($t=6.18$, $p<.001$). However, more rooms (a parcel with eight or more rooms) is associated with more summer cooling electricity use but its effect is marginally significant at the 0.1 level ($t=1.72$, $p<.1$). A parcel with a half-plex ($t=-3.06$, $p<.01$) or planned unit development ($t=-6.20$, $p<.001$) is likely to use less cooling electricity use in summer compared to a parcel with a single family home in a subdivision. As expected, a parcel with two single family units is associated with higher electricity use for summer cooling compared to a parcel with a single family home in a subdivision ($t=2.91$, $p<.01$). A parcel with a pool is likely to use less summer cooling electricity than the one without a pool ($t=-2.41$, $p<.05$). A parcel with a composite shingled roof tends use more summer cooling electricity use than the one with a wooden roof ($t=2.60$, $p<.01$).

Most importantly, the results reveal the contextual effect of urban form factors that I am interested in. Controlling for occupant behavior, demographic & socioeconomic status and property condition, population density, street orientation composition, certain variables of green space cover and tree heights with some configuration appear to have a significant impact on summer cooling electricity use. Higher population density is associated with a lower amount of summer cooling electricity use ($t=-2.47$, $p<.05$). Compared to streets that run east and west, other street orientations including north-south ($t=3.37$, $p<.01$), northwest-southeast ($t=3.31$, $p<.01$) and northeast-southwest ($t=3.56$, $p<.001$) tend to contribute to a higher use of summer cooling electricity. Green space density in a 500ft radius and water body density in both a 100ft and a 500ft radius do not show statistically significant effects. However, green space density in a 100ft radius shows a statistically significant association and appears to have a negative effect on summer cooling electricity use ($t=-3.98$, $p<.001$). In addition, a greater sum of tree heights planted on east, south and west sides of houses within a 60ft radius buffer is associated with a lower summer cooling electricity use. In contrast, sum of tree heights on the north side of a house does not show a significant effect. Among east, south and west configurations the effect of trees planted west of a house is most significant at the 0.001 level ($t=-3.77$, $p<.001$) while east and south configurations are significant at the 0.05 level.

Table 3.12 Standardized regression coefficients (beta) of Model 5

	Coefficient in Model 5	Beta
Occupant Behavior (& System Efficiency) Characteristics		
Ln(Baseline Electricity Use)	.727***	.527
Demographic & Socioeconomic Characterisitcs		
Percentage of White	-.030	-.009
Racial Diversity Index	-.053	-.009
Percentage of Bachelor's degree or higher degree	-.181***	-.043
Ln(Net Assessed Property Value)	.015	.015
Homeownership	-.095***	-.060
Property Condition Characteristics		
Built Before 1960	.088***	.054
Built After 1983	-.062***	-.042
Two story house	-.011	-.007
Ln(Total Floor Area)	.194***	.089
Three to Five Rooms	-.001	-.001
Eight Rooms or More	.027†	.017
Garage Area	-.000	-.008
Two Single Family Unit	.196**	.010
Duplex	-.029	-.008
Halfplex	-.084**	-.025
Nonsubdivision	.065	.0035
Planned Unit Development	-.241***	-.045
Pool	-.040*	-.023
Roof with Wood Shake/Shingle	.004	.002
Roof with Composition Shingle	.051**	.027
Urban Form I (Community Layout) Characteristics		
Ln(Population Density per Acre)	-.039*	-.025
Ln(Dwelling Unit Density per Acre)	.014	.007
Northeast-Southwest Street	.053***	.029
North-South Street	.042**	.028
Northwest-Southeast Street	.048**	.027
Urban Form II (Land Cover & Neighboring Vegetation) Characteristics		
Green Space Density in 100ft radius	-7.006***	-.040
Green Space Density in 500ft radius	.353	.001
Water Bodies Density in 100ft radius	-36.000	-.015
Water Bodies Density in 500ft radius	7.715	.013
Sum of Tree Heights in the East of Property within 30ft	.002	.011
Sum of Tree Heights in the South of Property within 30ft	.001	.009
Sum of Tree Heights in the West of Property within 30ft	.002	.014
Sum of Tree Heights in the North of Property within 30ft	-.001	-.012
Sum of Tree Heights in the East of Property within 60ft	-.002*	-.017
Sum of Tree Heights in the South of Property within 60ft	-.001*	-.019
Sum of Tree Heights in the West of Property within 60ft	-.002***	-.034
Sum of Tree Heights in the North of Property within 60ft	-.000	-.007
Constant	-.221	
R^2	0.311	
F-value	126.64	
N	13709	

3.7 Conclusion and Discussion

This study aimed to investigate the impact of urban form on summer cooling electricity use. Sacramento, California is used as a case study where I generate a data rich model that includes electricity billing data and a number of other predictors that represent occupant behavior, demographic and socioeconomic status, property condition and urban form. Various spatial analysis using GIS and LiDAR data are performed in order to extract those variables. Using multivariate analysis, I assess the effects of urban form variables on summer cooling energy use in Sacramento.

Among five factors that represent predictors of cooling energy use, occupant behavior (that includes the energy efficiency of non-cooling related electric devices) is the single dominant factor that explains 28.9% of the variance in the response variable. Its effect on summer cooling energy use is exclusively greater than those of other predictors. This is not a surprising result because occupant behavior has been known to play a significant role in energy consumption. An occupants' regular energy use pattern for everyday life is likely to be directly related to their energy use for air conditioning. According to Baker and Steemer (2000), occupant behavior and system efficiency account for a two-fold variation in energy consumption, which possibly contributes a four-fold variation in energy consumption.

Although the effects are not as large as occupant behavior, some variables of socioeconomic status and property condition also show statistically significant associations with summer cooling energy use. Higher education attainment level and homeownership are significantly associated with less use of summer cooling electricity. I suspect that occupants with higher education levels are more exposed to the rational for energy conservation and environmental education. Homeowners may have more control in improving the energy efficiency of a property (e.g. more efficient windows and insulation) in comparison to tenants. The energy efficient design and treatment, which might be correlated to homeownership, is missing in this model. In this regard, homeowners may tend to live in more energy efficient homes, thus resulting in less use of summer cooling energy.

Many variables that represent property conditions show statistically significant associations with summer cooling energy use. Houses built since 1984 (versus houses built before 1983), wooden roofs (versus asphalt composition shingles), smaller total floor area, housing types with half-plex or planned unit development (versus single family subdivision) appear to reduce summer cooling electricity use. These findings are comparable with previous research findings where the adaptation of building codes, wooden roofs, smaller house size and attached housing units contribute to less space-conditioning energy consumption. The effect of a pool shows an interesting result. As seen in Figure 3.27, the range and mean of houses with pools show higher summer cooling energy use compared to those of houses without pools. However, after controlling for other variables, a parcel with pools is associated with less summer cooling energy use. I suspect that swimming in a pool may serve as an alternative way of avoiding the heat in the home.

Quantifying the contextual effect of urban forms on summer cooling energy use is the unique contribution of this research. Controlling for other variables, higher population density, east-west street orientation, higher green space density within a 100ft radius, a higher sum of tree heights on the east, south and west sides of houses appears to have statistically significant effects and contributes to reducing summer cooling energy use. Most interestingly, among east, south and west configurations, trees planted west of a house show the most significant effects compared to those of trees planted in other directions. While comparing standardized regression coefficients (beta) for each tree configuration, I conclude that trees planted on the west side of the house have about a two times greater effect on saving summer cooling energy use than those planted on the east side of a house and have a 1.8 times greater energy saving effect than those planted on the south side of a house. This finding is comparable with Hildebrandt and Sarkovich (1998)'s assessment of the cost-effectiveness of SMUD's tree shade program. Hildebrandt and Sarkovich (1998) report that the average benefit for each tree planted on the west sides of houses ($120) is estimated to be nearly three times greater than the average benefit for all trees planted throughout the entire shade tree program ($39).

This study reveals that urban forms have a statistically significant impact on saving cooling energy use. The effects of these urban form variables appear to be trivial at an individual parcel level compared to other contributors like occupant behavior. However, the findings of this research support that optimized community layout and vegetation planning would have a significant contribution for macro-scale environments over a long term. In this regard, the results of this study have significant implications for research and practice on the building of energy efficient neighborhoods. More incentives and regulations are imperative not only for a single building but also for neighboring environments on a community scale. Rezoning for more attached housing with higher density and more green space, maximizing east-west street orientation, regulating floor area ratio and lot coverage for solar access and incentives for appropriate tree planting can be effective tools for encouraging energy efficient neighborhoods.

Even though I include a number of relevant variables, the model still lacks significant determinants that may strongly affect summer cooling energy use. For example, the inclusion of information with regards to glazing ratio, the energy efficiency of HVAC systems, and insulating walls, roofs and windows would significantly improve the explanatory power of the model. This information requires a significant amount of time and effort to collect field data and/or survey. However, for future studies, the inclusion of these variables would be rewarding in order to build a more concrete empirical model. Furthermore, more rigorous analysis of urban form extractions, especially for vegetation shapes and volumes will contribute to a better teasing out of the impact of vegetation. In this study, the sum of tree heights within a 30ft buffer for all configurations shows statistical insignificance. This result may stem from the limitation of current methods. For example, treetops, especially trees with large crowns, may not be detected in the 30ft buffer, although most of the volume of the crown is within the 30ft buffer zone from the house. The advancement of tree volume extraction would overcome this kind of problem.

IV. Urban Form and On-site Solar Energy: Assessment of the Effect of Trees on Residential Solar Photovoltaic Potential in San Francisco, California

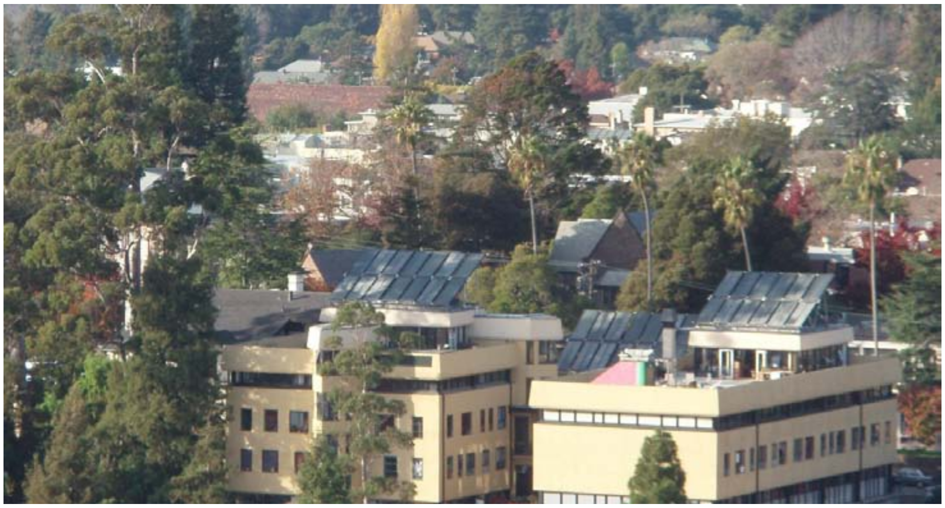
4.1 Introduction

On-site solar energy generation in urban settings (through rooftop PVs in most cases), like space-cooling energy use is also limited by spatial structures including: topography, rooftop aspects and shade from neighboring buildings and trees (Figure 4.1). Above all effects, the impact of trees on rooftop PVs (Figure 4.2) is complicated because urban trees provide various benefits, including mitigating urban heat island effect and saving energy. Chapter III concluded that trees on the east, south and west sides of houses have a significant impact on reducing space-cooling energy use. However, their potential counter impact on other green technologies (here, the rooftop solar energy generation) has rarely been investigated.

Given these interesting conflicts, Chapter IV investigates the association between urban form and on-site solar energy potential, focusing on the effect of trees on residential rooftop solar radiation. It aims to develop an approach to quantify the effects of trees on rooftop PVs potential on a civic scale. I chose the City of San Francisco as the study site because San Francisco contains a rich data set comprised of various typologies of buildings and trees. The results demonstrate the spatial patterns of the impact of trees on rooftop solar radiation and provide empirical evidence for crafting municipal solar energy planning, tree management and conflict resolution strategies. This method can be useful in implementing citywide solar energy planning.

Figure 4.1 Barriers of rooftop solar energy generation from spatial structures

Figure 4.2 Shade on rooftop PVs from neighboring trees



PVs are facing south but a giant tree blocks the solar access from the south-west in the afternoon, the most critical point of solar radiation during a day. Source: taken by the author.

4.2 Background

In the section 2.2.3, I reviewed previous literature that investigates the effect of trees on rooftop solar potential. In this section, I focus on various methods of solar potential assessment. The Solar potential estimation started with architectural simulation that assesses solar radiation on building rooftops and façades (Compagnon 2004; Kristl and Krainer 2001). This approach is based on shadow casting methods that capture the effect of neighboring structures. Although simulations are advantageous in testing the effect of selected building configurations on the solar potential of buildings, they are very limited when evaluating real environmental settings on a broader scale.

As a way to supplement the limitations of an architectural approach, GIS-based assessment has emerged for a broader scale analysis in the urban context. Unlike architectural simulations, GIS-based methods seek a more generalized and automated solution for a larger scale analysis. Gadsden et al. (2003) demonstrates the underlying methodologies of a solar energy planning (SEP) system. SEP software automatically calculates the area and orientation of each roof plane. However, their model is limited to two-dimensional (2-D) space and is not able to capture the inclination and shading of the roof planes without the assistance of a site survey. Hofierka and Kanuk (2009) built a three dimensional (3D) city model using an open-source GIS tool called *r.sun*, that was developed by Šúri and Hofierka (2004). However, this model only accommodates building features and still excludes the effects of non-building features like trees, which comprise a large component of urban infrastructure. Wiginton et al. (2010) and Vardimon (2011) extracted building footprints from ortho-photos and estimated regional scale solar PV potentials. However, both groups estimated the available rooftop areas using their assumption, which was based on previous studies. In summary, current GIS based assessments allow a broader scale analysis with an automated process, but the accuracy issue of estimation still remains.

Recently the use of Light Detection and Ranging (LiDAR) technologies has emerged as a solution for 2D GIS based solar mapping. The LiDAR data is based on the elevation information that is remotely sensed and collected by an airborne sensor, which provides highly detailed 3D surface models (x, y, and z coordinates) such as: terrain, buildings and vegetation. Therefore, the 3D surface models derived from LiDAR allow researchers to calculate the solar radiation on rooftops by taking into account the effects of neighboring buildings, trees, and topography without sacrificing broad scale. By characterizing residential rooftop shade, Levinson et al. (2009) reported that the loss of rooftop solar radiation due to trees and the buildings on neighboring parcels in well-treed 2.5 - 4km^2 residential neighborhoods, including Sacramento, San Jose, Los Angeles and San Diego, is about 10%. In 2011 the New York City Solar America City Partnership (2011) released the first city-wide solar map that was calculated using LiDAR (http://www.nycsolarmap.com/).

4.3 Study Site

I select the City of San Francisco for this study as it has a wide range of typologies of trees and buildings. Figure 4.3 shows that the population density of each study unit area ranges from 10 to 380 people per hectare. For example, the downtown area on the Northeast part of the map shows the highest population density with tall residential buildings with mixed land uses. In contrast, central hill areas are dominated by single family detached houses. Most residential areas in San Francisco are medium density with two to three story attached residential buildings.

With diverse population density, San Francisco also shows a wide range of tree density across its landscape (Figure 4.4). Due to its high building coverage and dense environment, most residential areas in San Francisco have low tree density. However, the residential properties around the central hills show a relatively higher tree density than the rest of San Francisco with large and tall trees.

Figure 4.3 Population density in San Francisco

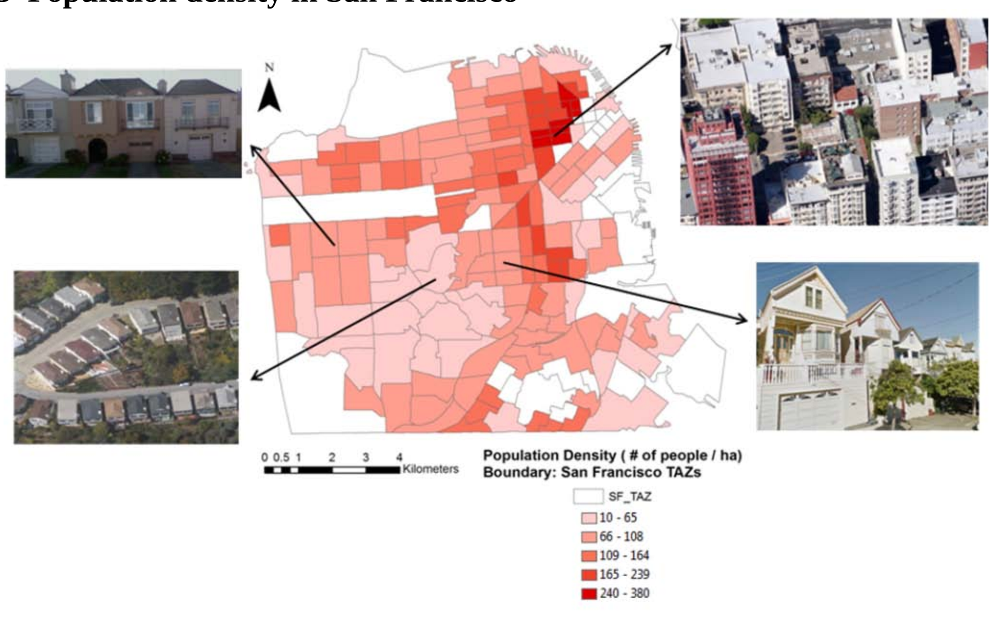


Figure 4.4 San Francisco consists of various urban settings. Images obtained using Google Map

4.4 Data Review

I obtain a Digital Elevation Model (DEM), Digital Surface Model (DSM) and building footprint polygons of the City of San Francisco from the San Francisco Department of Public Works. The DEM demonstrates the bare earth while the DSM shows all the reflective surfaces of San Francisco with a one-meter resolution, processed in 2007 by the Science Applications International Corporation (SAIC) (Figure 4). Building footprints and tree points are derived from the SAIC proprietary Automated Feature Extraction software that automatically detects and extracts features present in the LiDAR data. During the production process, building and tree features are automatically attributed with geometric information (lengths, widths, heights, area, etc). I obtain the parcel-level land-use map of San Francisco through the San Francisco Enterprise GIS Program (City and County of San Francisco 2008).

Figure 4.5 Digital Elevation Model (DEM) and DSM derived from LiDAR

4.5 Analyses

4.5.1 Calculating the Impact of Trees on Residential Rooftop Insolation

In order to calculate the difference between rooftop solar radiation with trees and the one without trees (Figure 4.6), I create a DSM without trees (Figure 4.7). In this DSM the elevation inside building footprints is assigned from the original DSM whereas elevation outside building footprints is given from the DEM (the bare earth). I calculate the incoming annual solar radiation (direct and diffuse) within ArcMap 9.3.1 using the original DSM and the one that eliminates trees (Figure 4.8). This method incorporates the physical conditions of each roof and includes shade from neighboring structures and trees. After these calculations I select the rooftops with “residential” and “mixed-residential” categories of land use by using the parcel-level land-use data set of San Francisco.

Figure 4.6 Calculating the impact of trees on residential rooftops

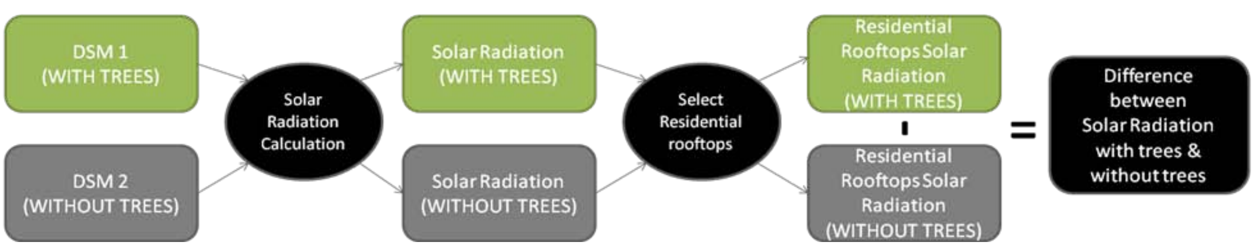


Figure 4.7 DSM, San Francisco (with trees & without trees)

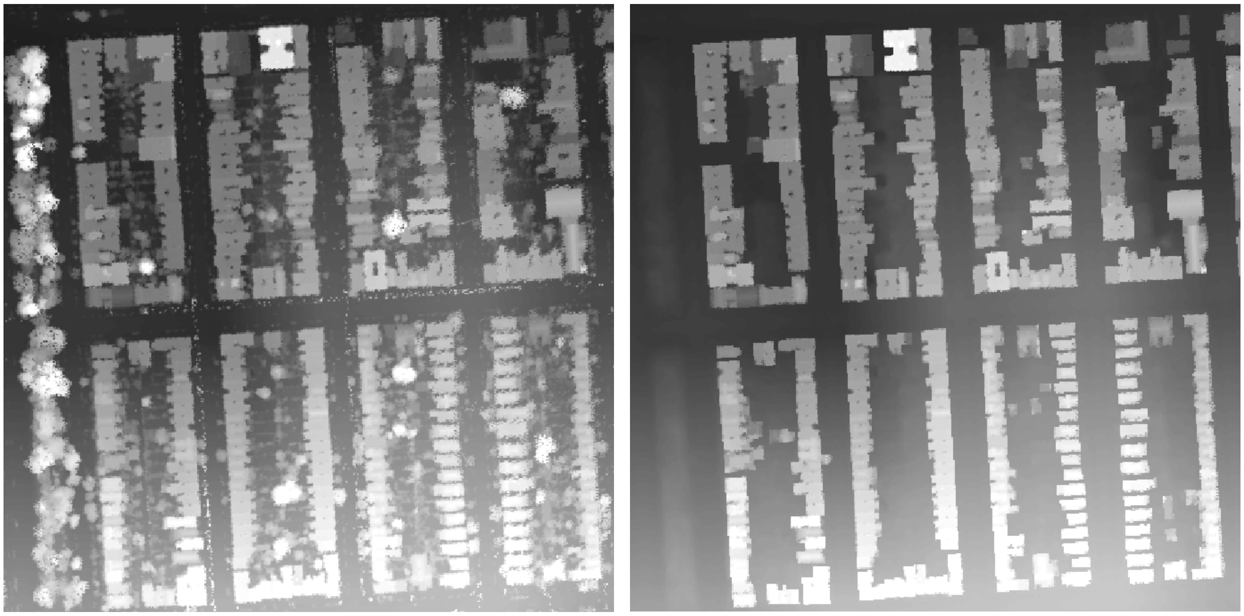
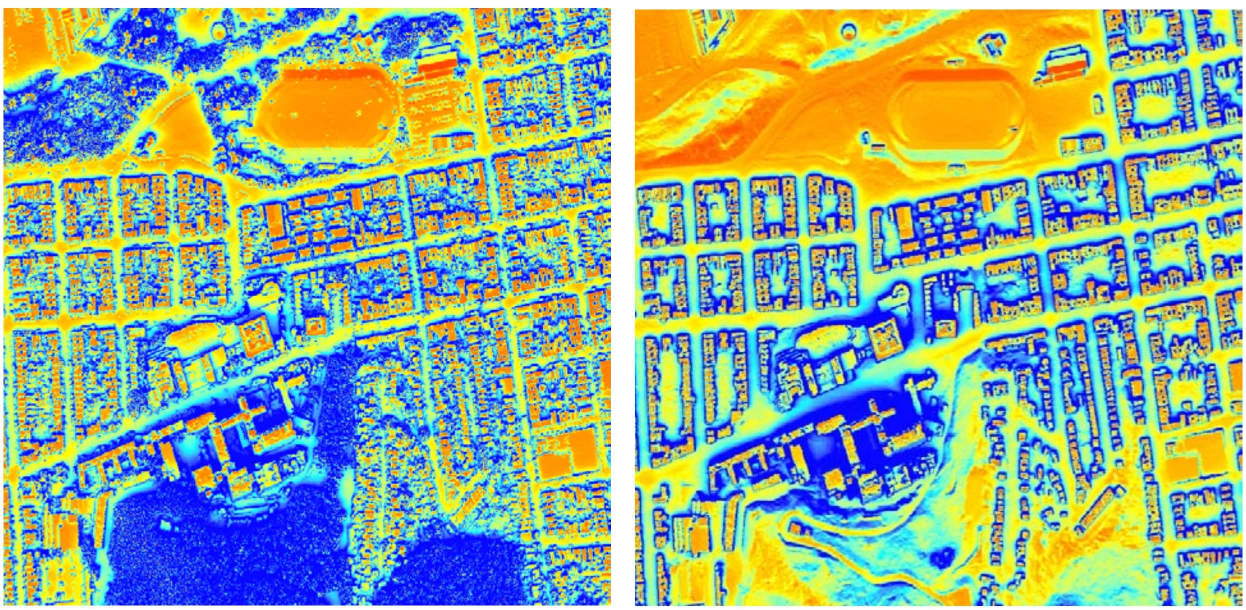


Figure 4.8 Solar radiation (Insolation) analysis (with trees & without trees)



4.5.2. Statistical Analysis

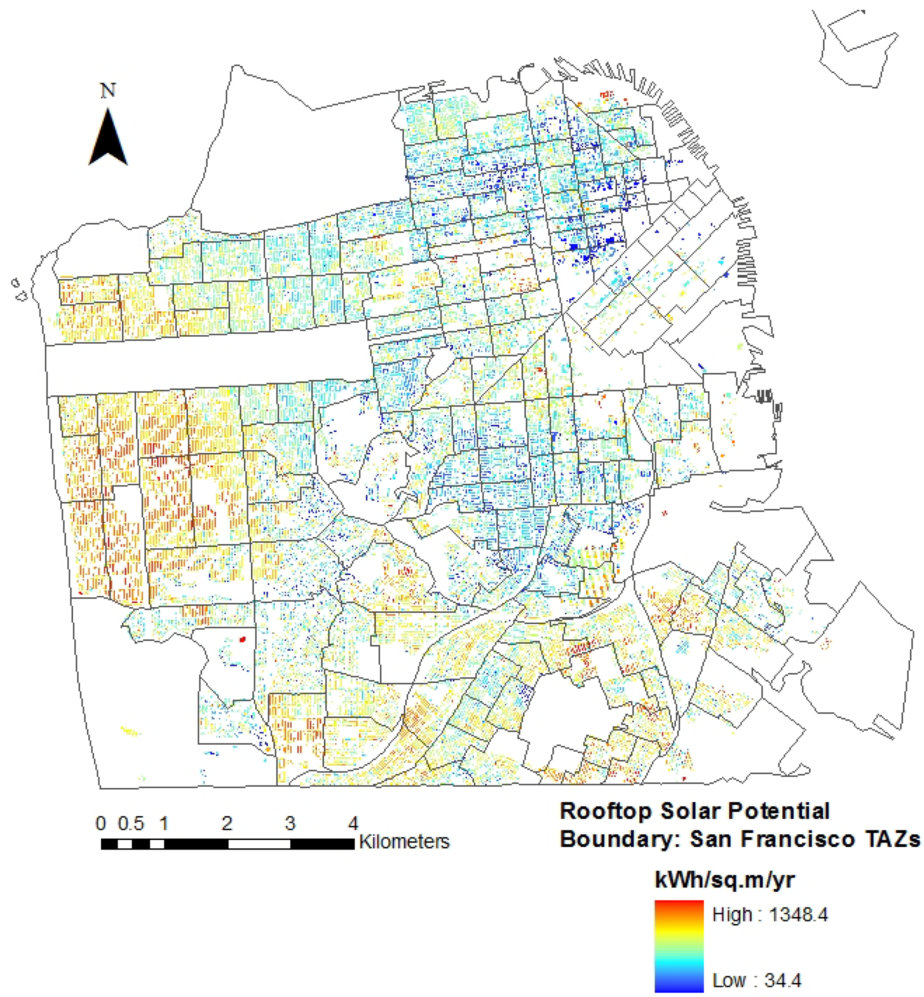
After calculating the rooftop insolation reduced by trees I perform a multiple regression analysis to see what attributes of trees affect rooftop insolation. I use 33 neighborhoods in San Francisco as study units and assess the impacts by neighborhoods. As predictor variables I include the average tree heights, the variance of tree heights and the tree density (number of trees per hectare) of neighborhoods. A response variable is the average reduced rooftop insolation of each neighborhood.

4.6 Results

4.6.1 Calculating Residential Rooftop Insolation

Figure 4.9 illustrates residential rooftops solar radiation (insolation) in the City of San Francisco. The insolation shows a wide range from 34.4 kWh/m^2/year to1348.4 kWh/m^2/year. Overall, the central and the northwestern part of San Francisco show lower insolation potential compared to the west and south parts of the city. The extremely low values in the Northwestern part (Downtown and Financial Districts) appear to be due to the shade from neighboring skyscrapers with various heights. The highest insolation levels are found in the western and southern parts of the city, that consist of homes with uniform building heights and high building coverage (as shown in Figure 3)[1].

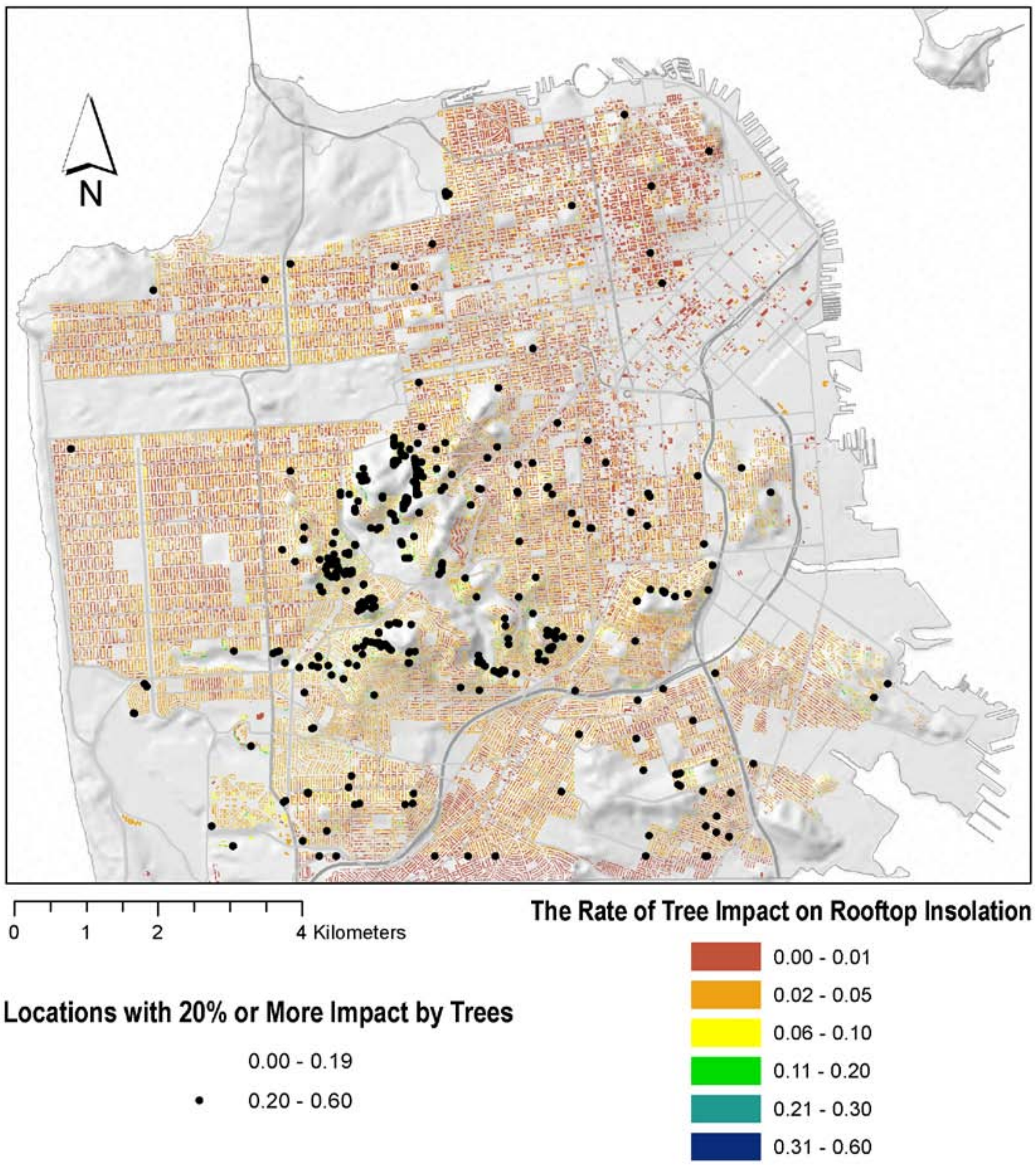
Figure 4.9 Residential rooftop insolation in San Francisco, California



[1] When incorporating monitoring data, the rooftop solar radiation in western San Francisco may show lower insolation values than those illustrated on the map. Geometrically, their roofs are certainly exposed due to uniform building heights and low tree density but the direct sun is blocked by fog more than in the eastern parts of the city.

Figure 4.10 displays the impact of trees on the insolation of each residential rooftop over the topography. The map shows a wide impact range of trees from 0 to 60%. By conducting a spatial query, residential properties with a higher impact from trees (here more than 20%) are represented with dots. The impacts of trees on rooftop insolation appear to be concentrated on central hill areas.

Figure 4.10 Location of the rooftops with more than 20% impact from trees



4.6.2 Regression Analysis

Using multiple regression, I investigate what attributes of trees reduce rooftop insolation. I transform all continuous variables into natural log form in order to ensure linearity and moderate heteroscedasticity. I use a robust model that does not heavily rely on typical OLS assumptions. I also compute a standardized regression coefficient (beta) to compare the effect of each predictor on reduced rooftop insolation from trees. Table 4.1 indicates that all of the predictors – tree density, average tree heights and variance of tree heights – show statistically significant effects. A neighborhood with a higher tree density, a higher average tree heights and a higher variance of tree heights is likely to have more reduction in its average rooftop insolation (Figure 4.12 to 4.14). According to standardized regression coefficients (beta) of three variables, tree heights appear to have a greater impact on rooftop insolation than that of tree density and in addition, the variance of tree heights also appears to show the largest effect. In other words, although two neighborhoods have same average tree heights, rooftop isolation decreases more in a neighborhood with higher variance of tree heights. The model with these three predictors explains 67% of variation in the average reduced rooftop insolation by trees. Predictors' Variance Inflation Coefficients (VIF) range from 1.32 to 1.69, which indicates no serious collinearity detected in the model (Table 4.2). I also made detailed investigations of the impacts of the predictors using scatter plots and maps.

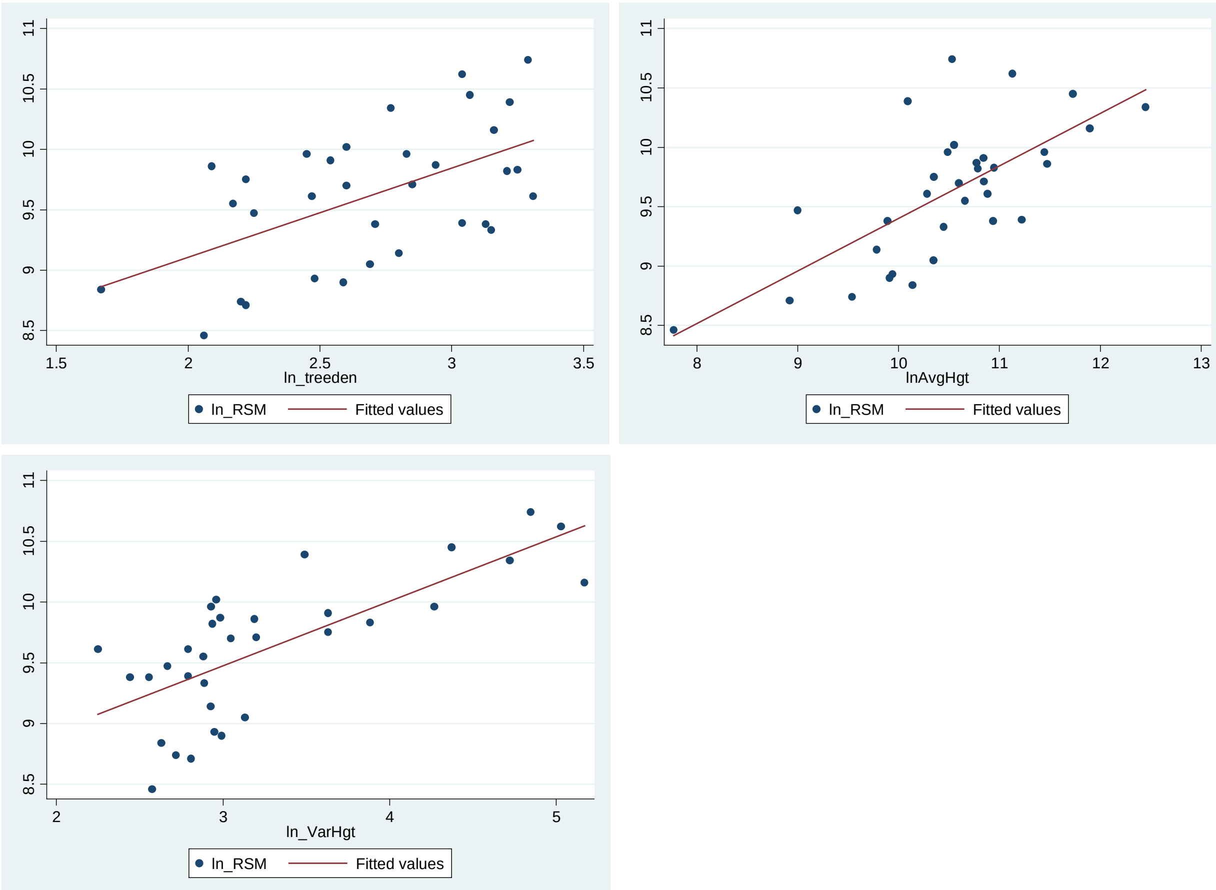
Table 4.1 The effects of trees on reduced rooftop insolation by trees

	Coef.	t	P-value	Beta
Ln(Tree Density)	.29	2.10	0.044	.22
Ln (Average Tree Heights)	.22	2.63	0.013	.34
Ln (Variance of Tree Heights)	.31	3.27	0.003	.43
Constant	5.55	8.45	0.000	.
R^2	0.67			
F	21.07			
N	33			

Table 4.2 Variance Inflation Coefficients (VIF)

Variable	VIF
Ln(Tree Density)	1.32
Ln (Average Tree Heights)	1.69
Ln (Variance of Tree Heights)	1.64
Mean VIF	1.55

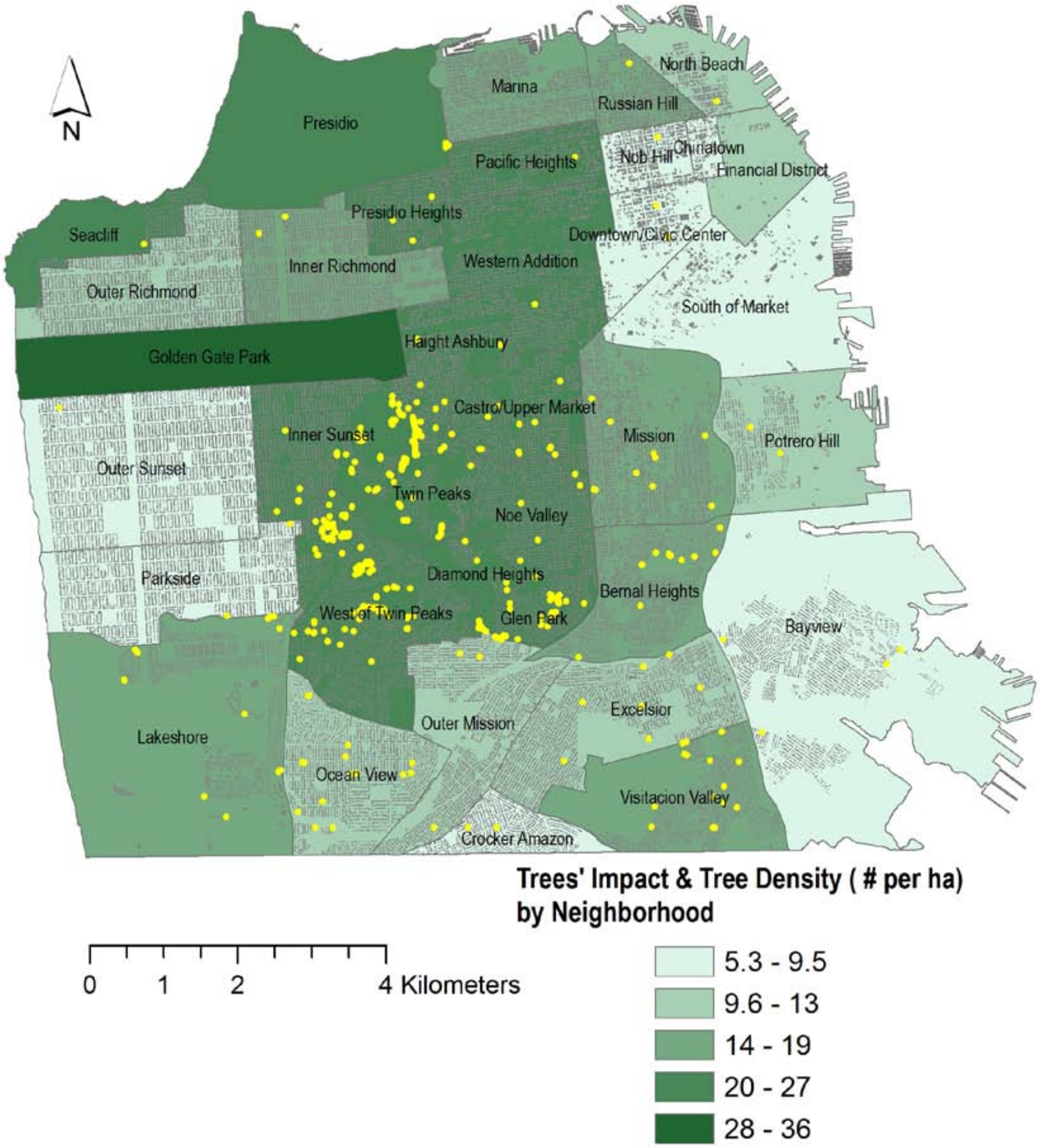
Figure 4.11 Average reduced rooftop insolation (Wh/m^2/year) over tree density (trees/ha), average tree heights (m) and variance of tree heights (m) of Neighborhoods



4.6.2 Spatial Analysis

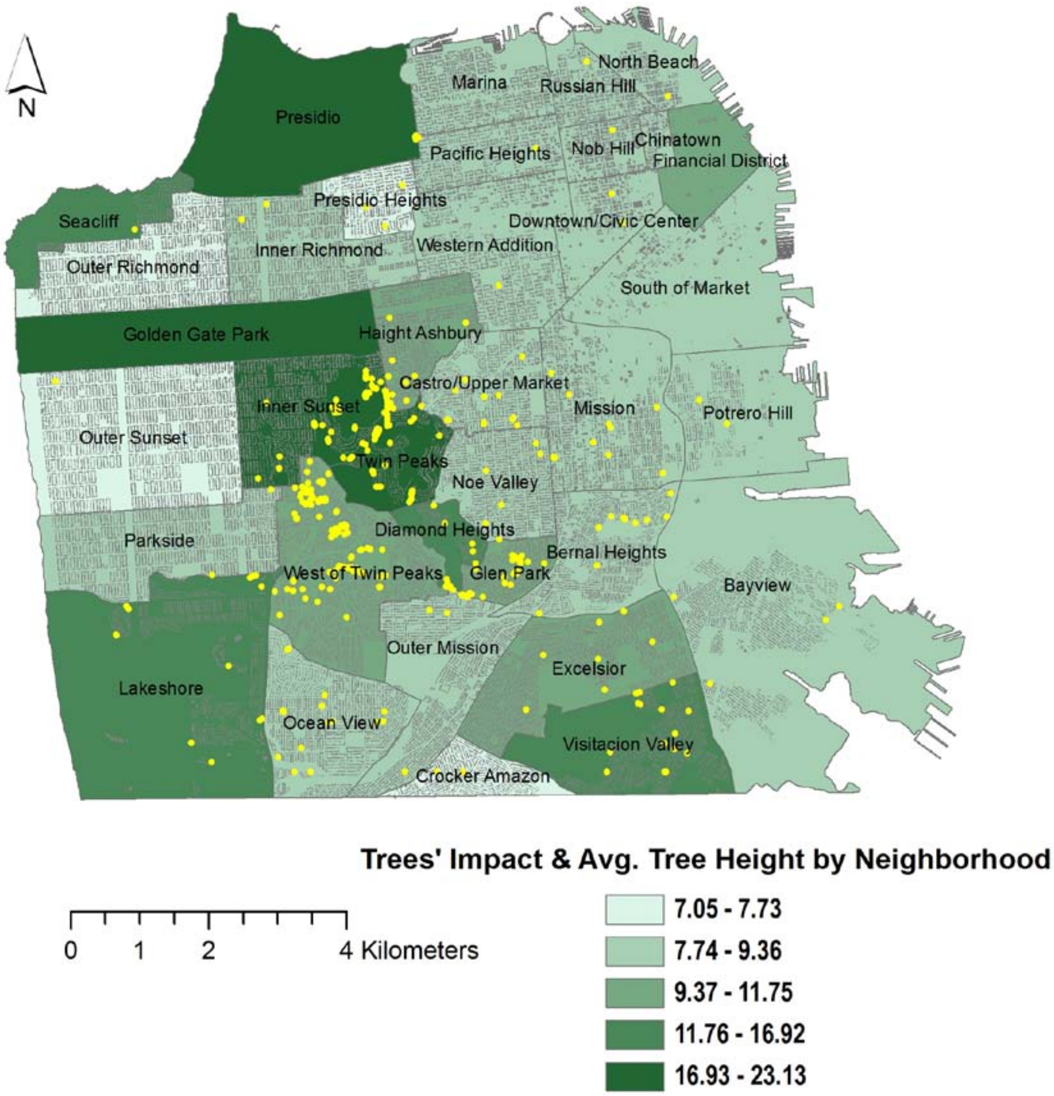
Such trends are also spatially illustrated in the maps. First of all, Figure 4.12 demonstrates that the tree density of neighborhoods is generally associated with the amount of insolation on the residential rooftops that has been reduced by trees. Neighborhoods with higher tree density (more than 20 trees per hectare), including the Inner Sunset, Twin Peaks and West of Twin Peaks, contain the most rooftop locations where the trees' impact is more than 20%. Some neighborhoods with high tree density, including Golden Gate Park, the Presidio and Seacliff, are exceptional cases because they are mostly open spaces and rarely contain residential units. Neighborhoods with commercial, business and industrial land uses like Downtown, the Civic Center, South of Market and the Bayview show a lower tree density, thus demonstrating a minimal impact from trees. The Outer Sunset and the Parkside (where the residential areas have a high building coverage) also show a minimal impact from trees. The average and the variance tree height add more detail in explaining the spatial variance from the impact of the trees (Figure 4.13 and 4.14). Twin Peaks and the Inner Sunset (where the highest average and highest vairance of tree heights are shown) include most rooftop locations that are affected by trees.

Figure 4.12 The impacts of tree density (number of trees per hectare) on residential rooftops



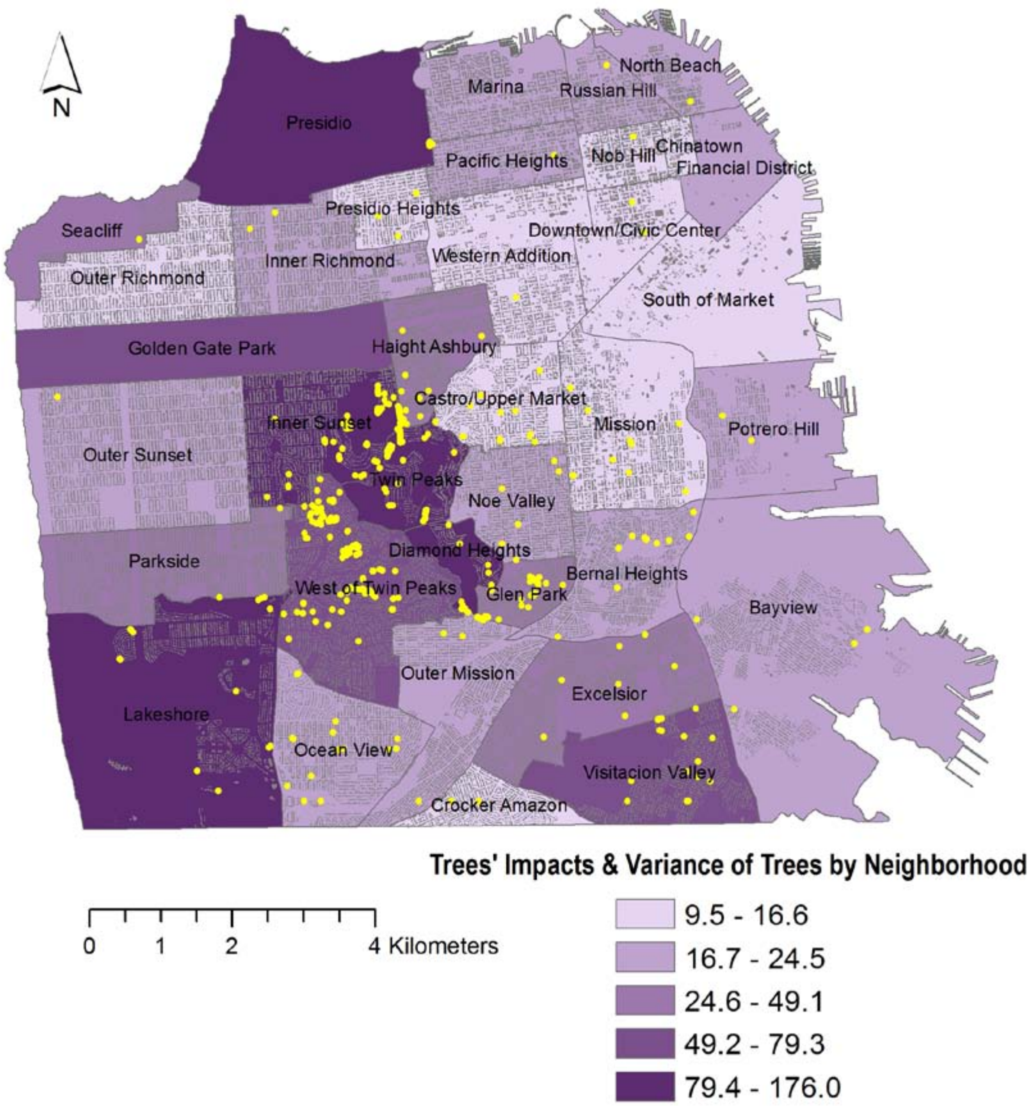
*Yellow dots are the locations of the rooftops with more than 20% impact from trees.

Figure 4.13 The impacts of the average tree heights on residential rooftops



*Yellow dots are the locations of the rooftops with more than 20% impact from trees.

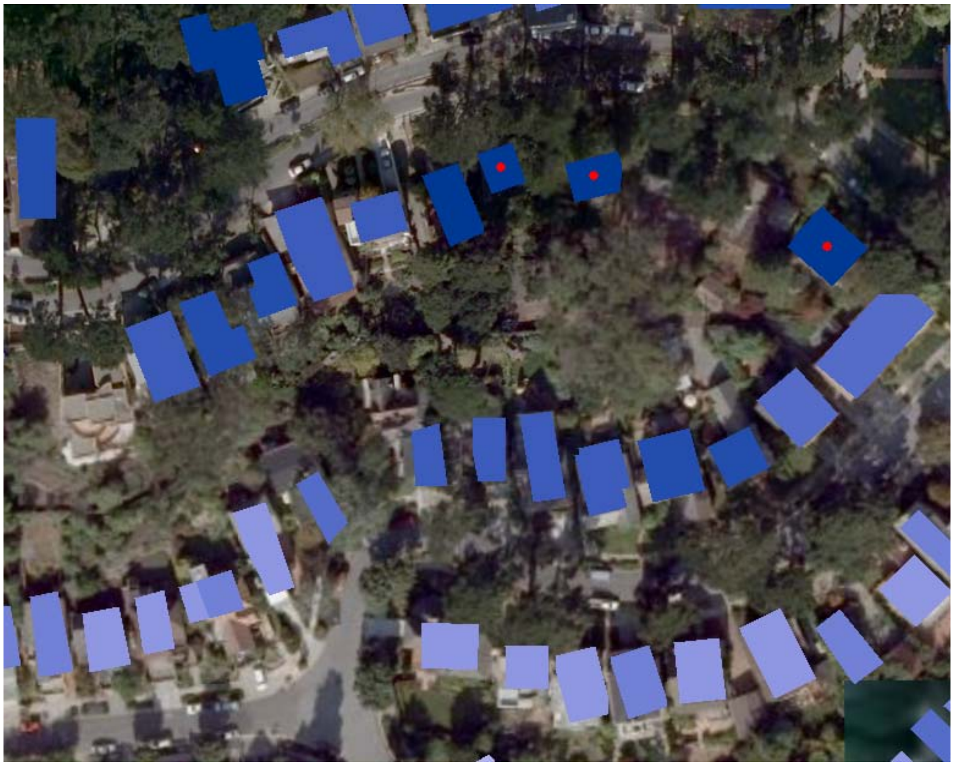
Figure 4.14 The impacts of the variance of trees heights on residential rooftops



*Yellow dots are the locations of the rooftops with more than 20% impact from trees.

Figure 4.15 shows the aerial photo and the map of a zoomed-in site that demonstrates the relationship between tree heights and rooftop insolation. Rooftops with lower insolation are surrounded by dense and tall trees.

Figure 4.15 Zoomed-in features of trees and rooftops



4.7 Conclusion and Discussion

This study investigates the impact of trees on residential rooftop insolation and demonstrates an approach to quantify and to spatially illustrate the impact on a citywide scale. Using spatial queries, it also demonstrates the spatial pattern of a certain level of impact across the city landscape. The result shows that rooftop solar potential is impacted not only by tree density but also by tree height. The result indicates that the variance of tree height as well as the average tree height has the greater impact than that of tree density. This result emphasizes the importance of utilizing data derived from three-dimensional modeling in order to conduct a more rigorous assessment.

Although this 3D model significantly improved the method, it should be noted that the model contains data quality errors. For example: trees information, such as, number of trees and tree heights may have errors because LiDAR may not fully detect the entire tree population. Since the data was generated through an automated process, the process detects taller trees with distinctive shapes better than smaller ones with less distinctive forms. This method also does a better job capturing the impact of surrounding trees than the ones whose crowns cover the roofs.

This method identifies the locations that would have potential solar access violations. California's Solar Right Act, Solar Shade Control Act, and Public Resources Code (25982) states the notion of "solar easement"— the right of receiving sunlight across adjacent properties for use by any solar collector. Given this current regulation, it is imperative to map the locations that would have solar access violations in order to manage potential conflicts between stakeholders including PV owners and tree owners. The results can also be linked to tree management programs. In the locations with high solar PV potential, municipalities can encourage home owners to manage their tree heights or to plant trees in optimal locations where trees would not conflict with rooftop PVs of their own and those of neighboring properties.

In the past few decades, mega-scale renewable energy generation facilities have shown significant environmental and social impacts on ecosystems and local communities (Johnson et al. 2002; Ko et al. 2011; Tsoutsos et al. 2005). Given these side effects, on-site distributed renewable energy generation (like rooftop solar PVs) is receiving more attention as a more sustainable way of generating energy. This study demonstrates one example of how on-site solar energy generation can be optimized. For future research more case studies that investigate sites with higher tree density (e.g. Sacramento and Palo Alto, California) should be undertaken and a comparative study of different cities will contribute to a variety of cases and impacts. Higher temporal resolution – the daily or seasonal changes of the impact – will provide more detailed implications. Comparing the impacts of trees on rooftop PV potential ("active solar") versus the cooling impact of tree shade ("passive solar") in a same site would contribute to a more comprehensive understanding of the benefits and the costs of trees in the residential energy sector. Rooftop PVs and trees can only make the best contribution towards achieving local climate action goals when they are optimally managed.

V. Tradeoff between Onsite Solar Energy Potential and Vehicle Energy Use over Density

In this chapter, I incorporate vehicle energy use in the definition of zero-net energy neighborhoods and address the trade-off between on-site solar energy potential and vehicle energy use across population density in the City of San Francisco. This study is the bridge between this dissertation and future studies, which aim to optimize urban forms by utilizing new green technologies.

5.1 Introduction

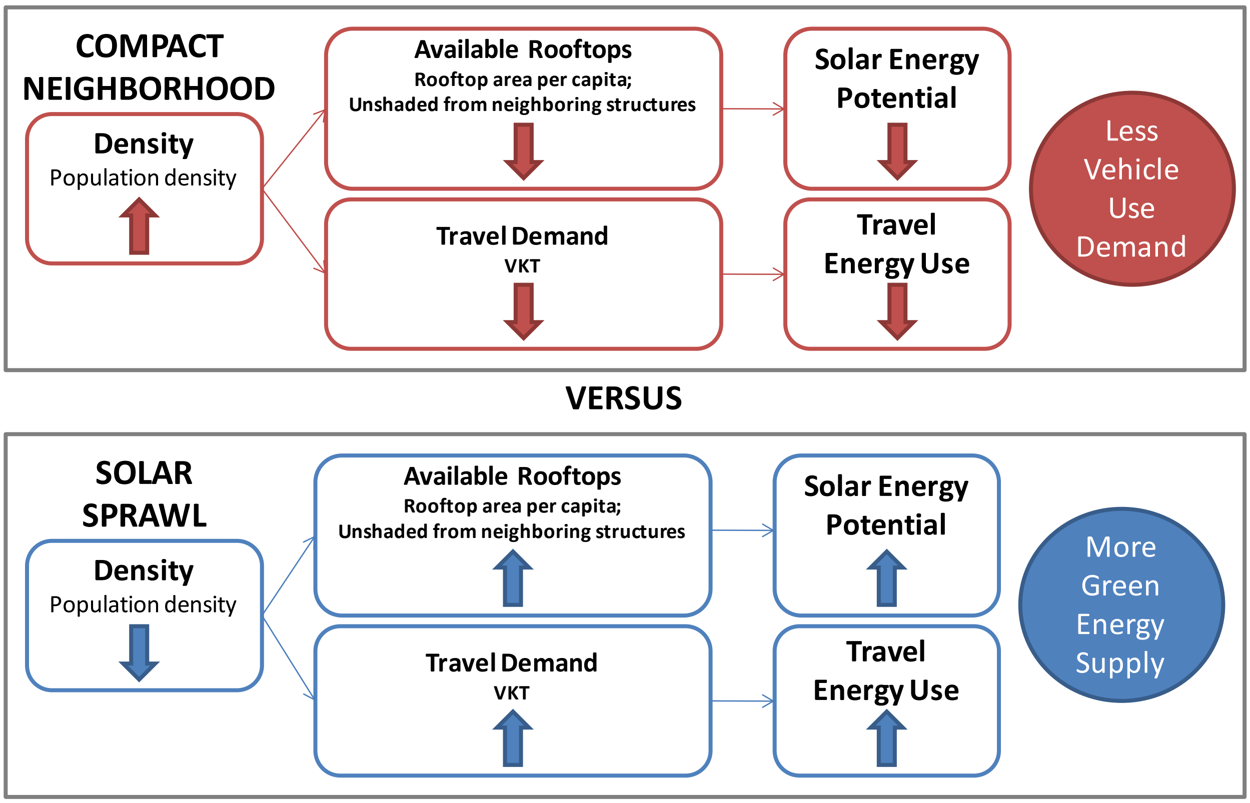
What level of density would be desirable to minimize greenhouse gas (GHG) emissions in cities? In the era of climate change and energy crisis, reducing GHG emissions through sustainable urban form is an imperative goal for many cities and states across the globe. In the U.S., compact development has been widely touted by city planners as a key to reduce fuel consumption for travel and its attendant externalities of sprawl: including air pollution, infrastructure cost and farm land loss. In 2006, California Assembly Bill 32 (AB32, the Global Warming Solutions Act) was passed with the aim of reducing GHG emissions to 1990 levels by 2020. One of the major means to achieve this target is controlling urban density and land use. Senate Bill 375 (SB375), also known as the anti-sprawl bill, was passed on January 1, 2009 in order to discourage vehicle use by promoting compact and infill development with mixed-land use and transit access.

Although an effort to promote higher density would serve to reduce vehicle trips, compact development may conflict with other initiatives for GHG emission reduction – such as maximizing on-site solar energy generation. Targeting 3,000 megawatts of solar energy systems for homes and businesses by the end of 2016, California initiated Go Solar California that provides 3.3 billion dollars of incentives to promote on-site solar energy. This state initiative influences the local climate action plan. For example, the City of San Francisco initiated its municipal solar incentive programs that are expected to reduce GHG emissions by 35,000 tons per year. As the earth's most abundant energy resource, on-site solar installations are projected to increase more radically as the solar photovoltaic (PV) efficiency improves and the cost per panel declines.

In general, on-site solar energy generation would likely benefit from a lower density environment where sparse built forms allow larger rooftop areas per capita for solar panels. In contrast, compact urban settings are likely to have more shade on the rooftops from neighboring structures, and provide less rooftop area per capita. As solar energy installations become more affordable and vehicle efficiency improves, the travel cost of suburban living may diminish. Advances in green technology may become an incentive for people to choose life in the suburbs, especially within the culture where people place more value on privacy and are accustomed to living in single-family homes.

Given this paradoxical challenge, several questions arise that this study seeks to answer here. Can California's goals toward compact cities and on-site solar power supplies avoid conflicts (Figure 5.1)? How much on-site solar energy can a low-density neighborhood generate over a compact neighborhood? Would the solar energy generated in the sprawl neighborhood be enough to compensate for their energy use caused by frequent and longer trips? How would the optimum density, which maximizes on-site solar generation and minimizes travel demand, change as solar panel technology and vehicle efficiency advances? To achieve California's aggressive goal for GHG emission reduction, the trade-off between the green initiatives must be evaluated.

Figure 5.1 Conceptual framework



5.2 Background

5.2.1 Vehicle Energy Use and Urban Density

The debate on the association between urban density and travel energy use began receiving a lot of attention after the well-known Newman and Kenworthy's study (1989). Surveying 32 major US and international cities, Newman and Kenworthy (1989) found that density has a significant impact on shifting travel patterns from cars to transit, thus contributing to reducing travel energy use. They concluded that doubling the density of a city reduced gasoline use per capita by 25 to 30 percent (Newman and Kenworthy 1989). Since then, many studies have examined the relationship between density and travel patterns such as: trip frequency, trip length, mode choice, travel demand (VMT) (Ewing and Cervero 2001) and transportation energy consumption (Mindali et al. 2004).

After decades of empirical studies and simulation models, much literature generally agrees that higher density is associated with lower levels of vehicle use per capita. Cervero and Kockelman (1997) included density as one of the three principal dimensions of the built environment that influence travel behavior. This has been referred to as the "three Ds" (density, diversity, and design) and later reorganized as the "five Ds", adding destination accessibility and distance to transit (Ewing and Cervero 2001, 2010) to the list. Ewing et al. (2008) argued that compact development has the potential to reduce VMT per capita by 20 to 40 percent over that of a sprawled development. Residential density, which is mostly measured using household, population, or dwelling unit variables, is reported to be negatively correlated with travel in the metropolitan areas of: Portland, Oregon (Parsons Brinckerhoff Quade and Douglas, Inc. 1993, 1994), San Francisco (Chatman, 2008; Holtzclaw, 1994; Holtzclaw et al. 2002), Los Angeles (Holtzclaw et al. 2002), San Diego, California (Chatman 2008), Chicago, Illinois (Holtzclaw et al. 2002), Austin, Texas (Zhou and Kockelman 2008), and other national surveys (Pickrell and Schimek 1999). These studies found that mixed land uses, more expensive parking, better transit and smaller households correlate with density and influence travel. Density can serve as a good proxy for the influential attributes for travel.

Density matters but its magnitude and independent impact are controversial and appear to depend on a specific form of built environment (Ewing et al. 1996; Ewing et al. 2008; Schimek 1996). Using meta-analysis, Ewing and Cervero (2010) reported that the weighted average elasticity of VMT with respect to household/population density was −0.04. As for the density type, inner area or Central Business District (CBD) density appears to have a more significant impact on travel energy use relative to outer area density and overall urban density, especially in European cities (Mindali et al. 2004; Naess et al. 1996).

5.2.2 Solar Potential and Urban Density

Urban density, with rooftop solar potential in mind, can be described in two ways: *household or population density* from the planning perspective and *compactness* from the design point of view. A neighborhood with high household/population density often corresponds to a compact neighborhood. For example, San Francisco depicts a relatively high household/population density along with high lot coverage across the city. In this regard, solar energy potential per person decreases as density (both household or population density and compactness) increases.

Like travel patterns, previous studies have agreed that on-site solar potential is also influenced by density. Higher household or population density implies that more people share rooftops, resulting in smaller available rooftops that are as accessible for on-site solar energy generation per person (Wiginton et al. 2010). Higher compactness indicates that buildings are "tightly" positioned on-site and likely result in smaller solar PV potential due to increased shade from neighboring structures. The effect of compactness on solar access is exacerbated when combined with irregular building heights and narrow street widths (Arboit et al. 2008). Architectural simulation assesses solar radiation on building rooftops based on shadow casting methods that capture the effect of neighboring built structures (Compagnon 2004; Kristl and Krainer 2001). GIS-based modeling is emerging for broader scale analysis in the urban context as it seeks a more generalized and automated solution (Carneiro et al. 2008; Gadsden et al. 2003; Hofierka and Kanuk 2009; Levinson et al. 2009; Nguyen and Pearce 2010; Rylatt et al. 2003; Vardimon 2011; Wiginton et al. 2010).

5.2.3 Ambivalent Effects of Urban Density on Travel Demands and On- site Solar Potential

Since both available rooftop area and vehicle travel increase as density decreases, a conflict between promoting on-site solar energy generation and reducing vehicle travel appears to be growing. O'Brien et al. (2010) examined how the net energy use (a combination of solar energy, household operating energy use, and transportation energy use) varies with housing density. They investigated three distinctive neighborhood types: low-density outer suburb with detached houses, medium-density inner suburbs with townhouses, and high-density inner city with high-rise multi-unit residential buildings. However, such a comparison among three representative housing forms was limited in showing the trend across a continuum of urban density. In addition, the neighborhood locations and their geometry were determined based on the assumptions that made them suitable for the calculation methods employed. As for the solar energy availability, all roofs were assumed to be flat. Although the O'Brien et al. (2010) study was meaningful as a first attempt in highlighting this issue, such a parametric approach needs to be improved and validated.

5.2.4 Scope of the Study

The focus of this study is the trade-off between solar PV potential and travel energy use. Unlike the O'Brien et al. (2010) approach, house operating energy consumption was excluded in this analysis by assuming that the housing energy consumption is independent of population density. Recent studies reported that the difference of house operating energy used for different housing types are minimal when controlling for other variables (Kaza 2010); such a difference is reduced in housing built after 1980, which adopts building codes and is more energy efficient (O'Brien et al. 2010; Holden and Norland 2005). Besides energy efficiency, the residential energy implications of densification are not clear due to the balance between the benefits of reduced heat loss and the costs from reduced passive solar heating and daylight availability (Steemers 2003). In order to overcome the current limitations, this study examines the rooftop solar energy availability and vehicle energy use for the entire city of San Francisco to show the trends across the range of the density.

5.3 Methodology

To demonstrate the trends of personal travel energy use and rooftop solar potential across a range of urban densities, this study first measures the total available residential rooftops for on-site solar photovoltaic panels and the total vehicle kilometers traveled (VKT) for each Traffic Analysis Zone (TAZ) in the city. The travel-related data is based on TAZ and shows a wide range of population density from 10 to 378 people per hectare. In order to avoid a bias in representing residential density, the TAZs that contain no (or very few) residential buildings are not included in the analysis.

5.3.1 Vehicle Energy Use Estimation[1]

For estimating vehicle energy used by residents within TAZs, VKT per capita is estimated based on the number of inter-zonal personal trips and multiplied by average fuel efficiency. VKTs generated by residents in TAZ *i* were estimated as the total distance traveled by vehicle trips generated from the TAZ, *i*:

$$VKT_i = \sum_k \sum_j \frac{T_k^{ij}}{p_k} \cdot D^{ij}$$

Where,

T_k^{ij} : The number of trips between TAZs *i* and *j* in mode *k*

D^{ij}: Shortest distance between TAZs *i* and *j* through the street network

P_k: The number of passengers in mode *k* (if single driver, $P_k = 1$, if carpool, $P_k = 2$, otherwise $P_k = 3$)

Any transportation mode (*k*) that generates vehicle trips can be considered. This study includes three modes: a solo driver, a carpool with two occupants, and a carpool with three or more occupants. The number of inter-regional personal trips, T_k^{ij} , between all pairs of TAZs by different transportation modes is estimated based on the Bay Area Travel Survey (BATS) 2000**.** In the trip table, the estimated number of personal trips is recorded for each origin-destination (O-D) pair where any trip exists.

Since travelers are likely to choose routes that minimize their travel times, the distance between a pair of centroids of O-D TAZs, D^{ij}, is calculated as the shortest path distance through the street network. Network Analysis in ArcGIS 9.3.1. is used to compute the shortest path distance for each pair of TAZs and the distance between each O-D pair and D^{ij} is derived. One possible error inherent in this method is the intra-zonal trips are not considered nor calculated as there is one centroid rendering $D^{ij}= 0$. These errors appear to be negligible for VKT estimation because: i) trip distance within the zone, compared to inter-zonal trips, is relatively short and ii) intra-zonal vehicle trips are relatively few when substituted by walking and bicycle use. The comparison between the total VKT estimated from this method and the county-level VKT estimated by the Metropolitan Transportation Commission (2011) is within 5%.Since the number of vehicular

[1] For this analysis, I used simulated vehicle trips calculated by Dr. Kitae Jang, an expert in traffic flow theory and transportation engineering, currently an assistant professor at the Korea Advanced Institute of Science and Technology.

trips is of interest but only personal trips are available, VKT was estimated by weighting the number of passengers in the vehicle. A solo driver creates one vehicle trip while carpool vehicles, serve two or more passengers with one vehicle trip. Therefore, personal trips, T_k^{ij}, are divided by the number of passengers in the vehicle in order to estimate the vehicle trips.

Finally, the amount of energy consumed using a linear relation between VKT and travel energy consumption is estimated. VKT is converted to the amount of gas consumed by dividing VKT by the energy efficiency (kilometer per kWh) *e* of the vehicles. Fuel efficiency values are taken within a range from a current average passenger cars' fuel economy (Bureau of Transportation Statistics, 2011) to the highest fuel economy in the market (Table 2). The equation of energy consumption by vehicles at TAZ *i* is:

$$E_i = \frac{VKT_i}{e}$$

5.3.2 Assessment of City-wide Solar Energy Potential

For the assessment of city-wide rooftop solar potential, this study use a Light Detection and Ranging (LiDAR) surface model and building footprint features of the city obtained from the San Francisco Department of Public Works. The LiDAR data is based on elevation information that is remotely sensed and collected by an airborne sensor, thus providing highly detailed 3D surface models (x, y, and z coordinates) such as: terrain, buildings and vegetation. This data depicts the reflective surface of all of San Francisco with a one-meter resolution Digital Elevation Model (DEM) processed by the Science Applications International Corporation (SAIC) in 2007 (Figure 5.2). Building footprint polygons used for this analysis are derived from the SAIC proprietary Automated Feature Extraction software that automatically detects and delineates features present in the LiDAR data. During the production process, features were automatically attributed with geometric information (lengths, widths, heights, area, etc). A publicly available parcel-level land-use map is used for filtering residential rooftops and obtained through the San Francisco Enterprise GIS Program (City and County of San Francisco, 2008).

Figure 5.2 Example of DSM derived from LiDAR, San Francisco

The rooftops with “residential” and “mixed-residential” categories in the land use are selected by using the parcel-level land-use map of San Francisco. The incoming annual solar radiation (direct and diffuse) from all the residential/mixed-residential rooftops is calculated in an ArcMap 9.3.1. This method incorporates the physical conditions of each roof and include shade from neighboring structures and trees. After calculating solar radiation values in GIS, the output values from our analysis are adjusted by employing the average insolation values from ground data (http://sfwater.org/cfapps/solar/solarmap1.cfm) monitored by the San Francisco Public Utilities Commission.[2] In addition to physical constraints, this study makes a conservative assumption that only 30% of calculated solar PV potential for each rooftop can be used for solar PV installation. Solar PV installers in this region require a building to meet certain criteria such as: the proper orientation (South, Southwest, and West for this location), slope (no steeper than 45 degree) and the minimum continuous surface area (about 12 to 20 sq meters). Finally, each rooftop’s solar potential is estimated by multiplying a PV efficiency rating as percent (Table 5.2).

Table 5.1 Variable description, data used, and their sources

Variables	Description	Data	Sources
Population density	Number of population /hectare in each TAZ	San Francisco Bay Area Traffic Analysis Zones (TAZ)	Metropolitan Transportation Commission
Rooftop areas per capita	Total rooftop areas/ number of population in each TAZ	Building footprints derived from LiDAR	San Francisco Public Utility Commission
Rooftop solar PV potential per capita	(Total rooftop solar radiation/ number of population in each TAZ) * PV efficiency * 0.3 (constraints)	Digital surface model and building footprints derived from LiDAR	San Francisco Public Utility Commission
VKT per capita	Total distance traveled by vehicle trips / number of population in each TAZ	Bay Area Travel Survey 2000	Metropolitan Transportation Commission
Vehicle energy use per capita	VKT per capita / vehicle energy efficiency	National Transportation Statistics	Bureau of Transportation Statistics

Table 5.2 Vehicle and solar cell efficiency options used in the analysis

	Vehicle Efficiency	Description	Solar Cell Efficiency	Description
Option 1	1.07 km/kWh	Average gasoline-based passenger car	11.1%	Currently emerging PV
Option 2	2.37 km/kWh	Hybrid vehicle	20.3%	Thin Film Technologies
Option 3	5.26 km/kWh	Plug-in hybrid electric vehicle	27.6%	Crystalline silicon
Option 4	6.76 km/kWh	100% electric vehicle	42.4%	Multi-junction concentrators

[2] Since this study adjusts the rooftop insolation by using the average insolation value from 23 monitoring stations in San Francisco, the absolute level of insolation is adjusted to the real world environment. However, the relative difference of insolation over San Francisco is mainly from geometric difference, not from climate. When accounting for weather, rooftop insolation in western San Francisco may show lower values than our estimates. Geometrically, their roofs are certainly exposed due to uniform building heights and low tree density but the direct sun is blocked by fog more than in the eastern parts of the city. However, exclusion of fog in the analysis appears to be more proper for this research goal in order to assess the “pure” effects of density on rooftop solar potential and vehicle trips.

5.4 Results

5.4.1 VKT and Rooftop Areas per Capita over Density

As described earlier, VKT per capita and rooftop per capita are two essential measurements that influence vehicle energy use and rooftop solar energy potential. Figure 5.3 illustrates the relationship between VKT per capita and population density. This figure suggests that VKT for a person drops moderately over the population density. The elasticity of VKT (*e*) with respect to population density is -0.005 and is quite low, however, it is within the range of the elasticity that has been reported from similar studies (0.00 to -0.12) (Ewing and Cervero 2010). From a similar study of Holtzclaw et al. (2002), I suggest that the impact of density on VKT captures those of other correlated variables such as: accessibility to local shopping, transit, and pedestrian and bicycle friendliness. I argue this mild trend reflects the physical attributes of San Francisco. Public transit and bike routes in San Francisco are relatively well distributed across the city compared to other areas in the U.S. This model shows an explanatory power (R^2 value of 0.136) similar to other vehicle use models where R^2 values are in the range of 0.03 to 0.2, even after adjusting for other variables (Cervero 1996; Cervero and Kockelman 1997; Chatman 2008; Kitamura et al. 2001; Zegras 2010). Figure 5.4 shows that a similar trend occurs in the rooftop areas per person and with population density. The elasticity of rooftop area with respect to population density is -0.004.This trend appears to be strong, especially in lower densities.

Figure 5.3 VKT per capita over population density

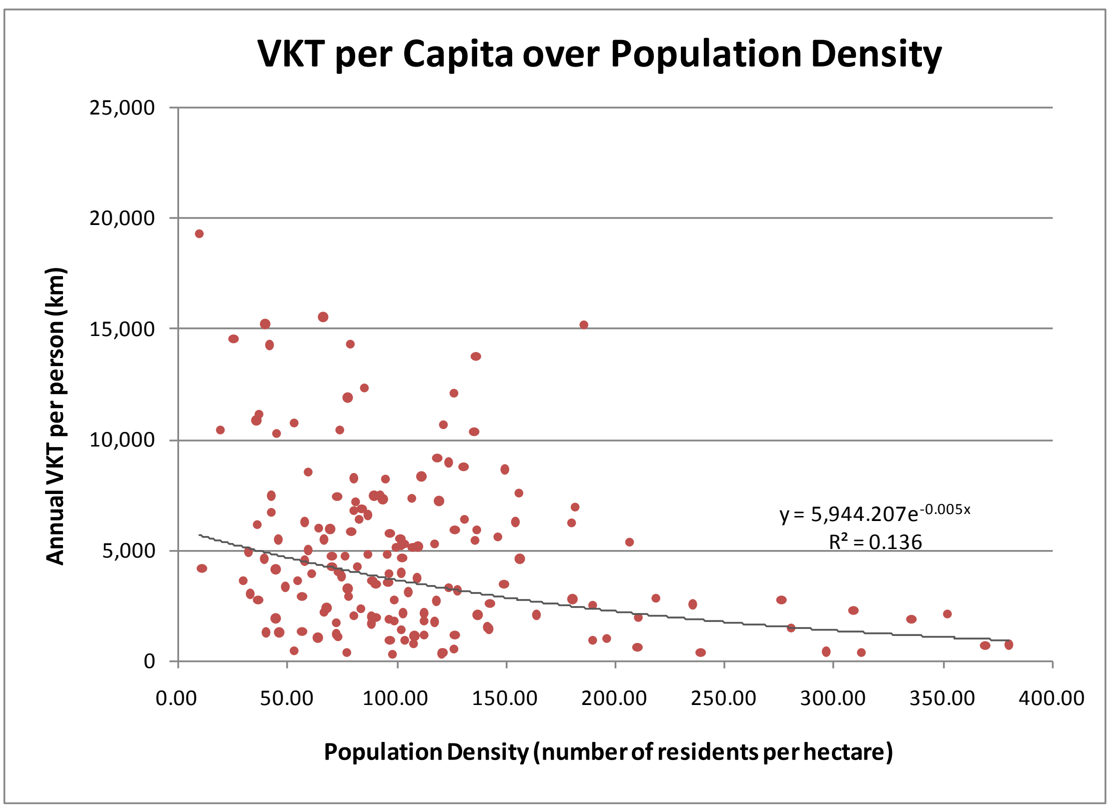
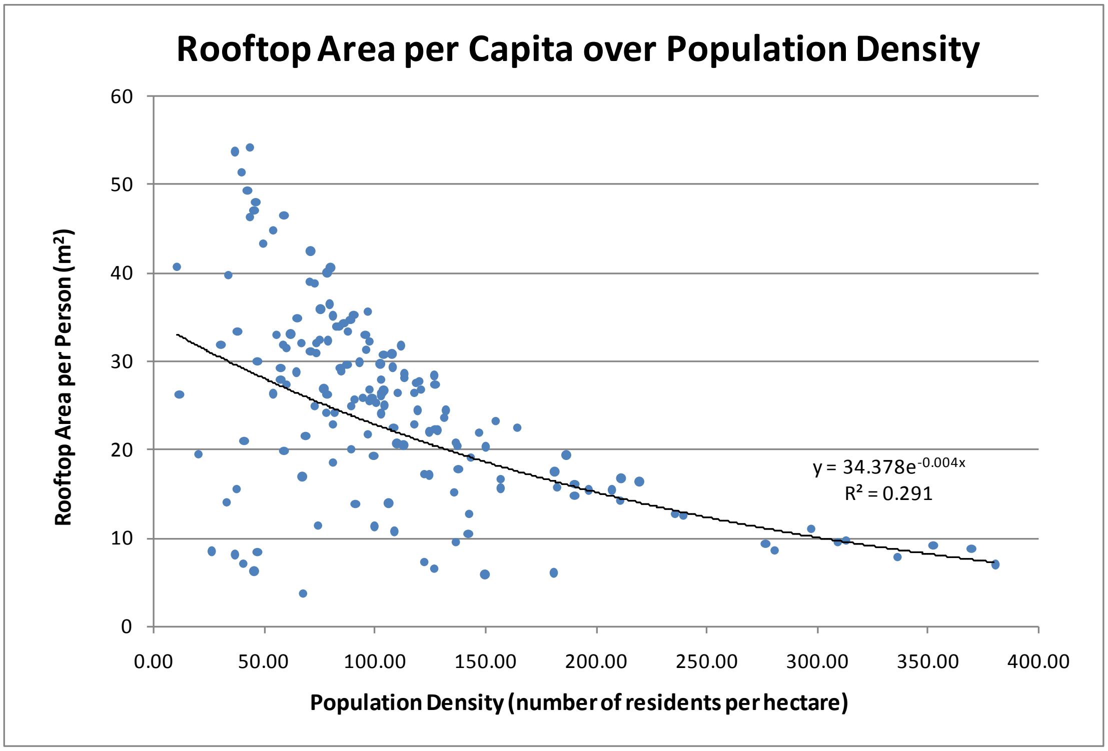


Figure 5.4 Rooftop per capita over population density



In the both plots there is a larger variation in the regions with lower population density. This variation can be explained by the variation within the analysis unit (TAZs); where some TAZs with large areas often include a wide range of spatially varying conditions, resulting in wide variation. For example, some TAZs with large areas with a few medium-density buildings and a large area of open space could result in an extremely low rooftop area per person with relatively low population density. This kind of case also causes a larger VKT per capita especially when the residents in those TAZs have less accessibility to transit systems.

5.4.2 Vehicle Energy Use and Rooftop Solar Potential over Density

To explore the effect of different levels of technologies this study used the estimated functions to predict vehicle energy use and solar energy potential per capita over the population density for various vehicle energy and solar PV efficiencies. Referring to Bureau of Transportation Statistics (2011), the U.S. Department of Energy and the Environmental Protection Agency's estimates (2011), I selected four vehicle efficiency options: 1.07 km/kWh for an average passenger car (which is equivalent to 22.6 MPG), 2.37 km/kWh for hybrid cars, 5.26 km/kWh for a plug-in hybrid electric vehicle and 6.76 km/kWh for a 100% electric vehicle. In addition, I selected four solar cell efficiency options using the Best Research-Cell Efficiency of the National Renewable Energy Laboratory (NREL) (Kazmerski 2010): 11.1% for currently emerging PVs, 20.3% for thin film technologies, 27.6% for crystalline silicon and 42.4% for multi-junction concentrators (Table 5.2).

Figure 5.5 illustrates the changes in vehicle energy use and rooftop solar energy generation per capita with eight combinations of technological options. The amount of energy consumed by vehicles or generated by rooftop solar devices significantly varies from about 100 to 6,000 kWh per person over density. As observed in the trends of VKT and available rooftops per person, both vehicle energy use and solar energy generation per capita decrease as population density increases. The decreasing rate varies depending on the technology. Three scenarios were explicitly compared and shown in Figure 5.6, 5.7 and 5.8: the current average technology scenario, the density threshold changes over technologies and the best current technology scenario.

Figure 5.6 displays the comparison between the trend of vehicle energy use and that of rooftop solar energy potentials per person given a combination of current technologies that are commonly implemented in current practice (1.07 km/kWh efficiency for an average gasoline-based passenger vehicle and 11.1% for solar PV efficiency). Vehicle energy use per capita exceeds energy generated by rooftop solar PVs per capita in all density ranges. However, the gap between vehicle energy use and rooftop solar energy generation is smaller as population density increases; since the rate of decrease in vehicle energy use is higher than that of solar energy generation. Given the current technologies, the result indicates that solar energy generated from rooftop PVs cannot compensate for the energy used by vehicular travel, especially in a range of lower density environments.

In the transition from the current to the advanced technologies, the intersecting points appear as the advanced vehicle and solar technologies penetrate into the market, indicating that vehicle energy use drops and solar energy generation increases. If we define a density threshold as the point of equilibrium between vehicle energy use and solar energy generation, (a kind of break-even point that the solar energy supply and vehicle energy use intersect on the figure) Figure 5.7 exemplifies that the density threshold can change based on the different combinations of technologies. For example, the density threshold of population density could be about 180 persons per hectare when we assume that there is a combination of 27.6% of solar device efficiency (crystalline silicon) and 1.07 km/kWh of vehicle efficiency (average gasoline-based passenger car). However, if we apply 11.1% of the current solar PV efficiency and 2.37 km/kWh of the current average of a hybrid vehicle, the density threshold of population density can shift to around 270 persons per hectare.

Figure 5.8 illustrates the best combination of advanced technology dominating the market and assumes the use of electric cars (6.76 km/kWh) and solar multi-junction concentrators (42.4%). This result indicates an opposite case that assumes the combination of current average technologies (Figure 5.6). Noticeably, solar devices can generate enough electricity that one person would consume for vehicle use over the entire range of population density. In other words, the amount of energy produced by rooftop solar devices exceeds that of energy consumed by vehicles and this pattern is more pronounced in the lower density environment.

Figure 5.5 VKT and Rooftop area per capita over population density

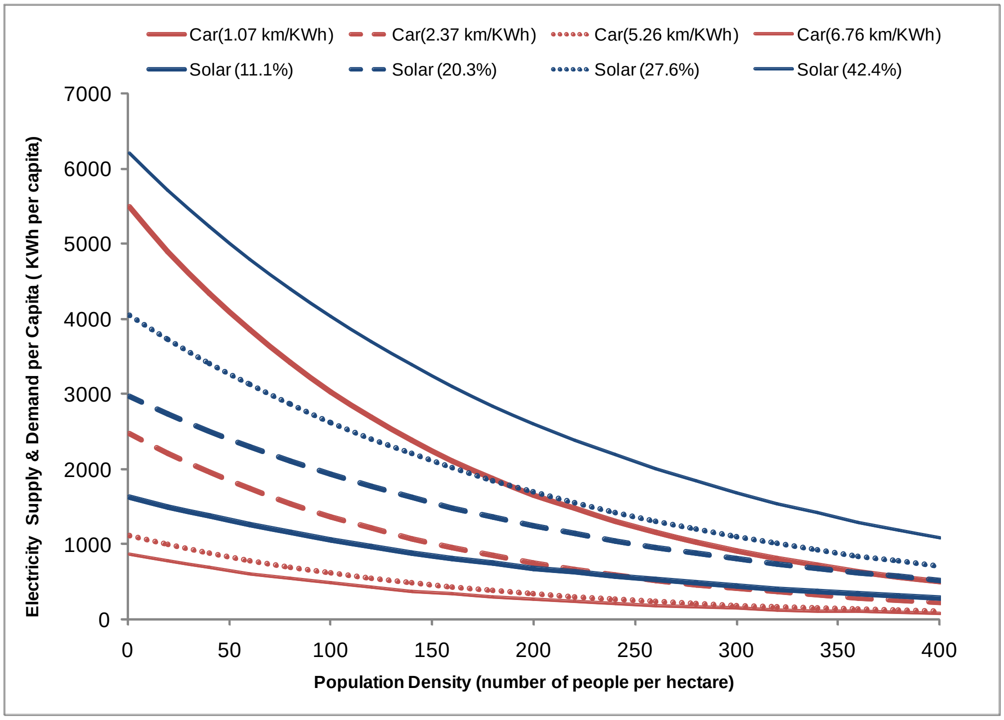


Figure 5.6 Vehicle energy demand versus rooftop solar energy supply per capita over population density at the current average technology scenario

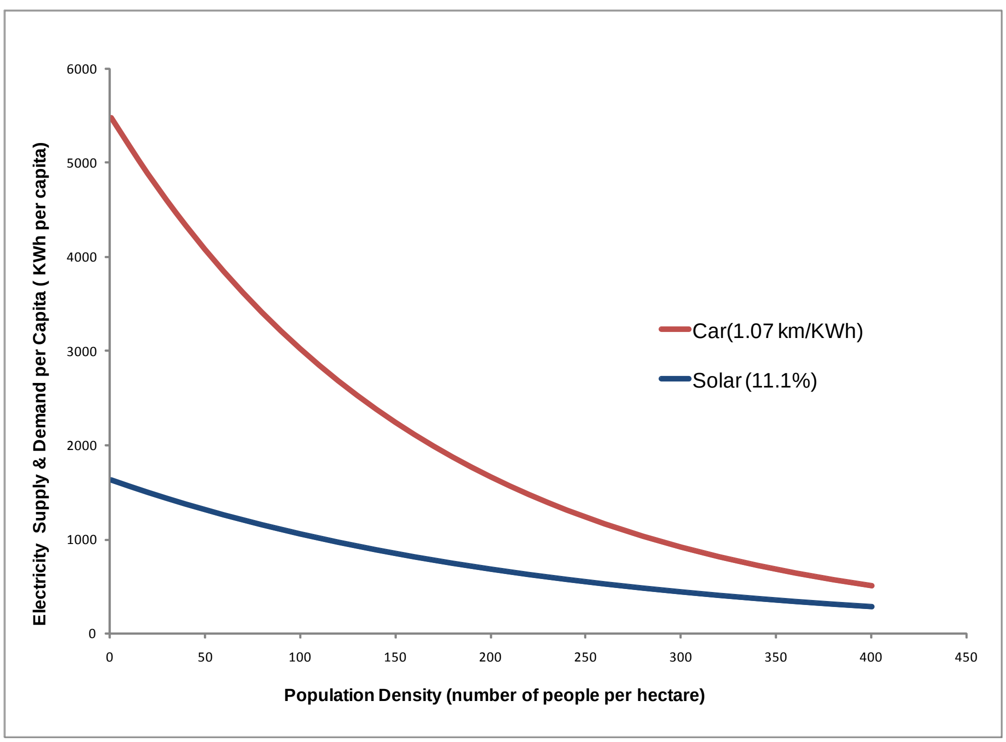


Figure 5.7 The example of density threshold by different combination of technologies

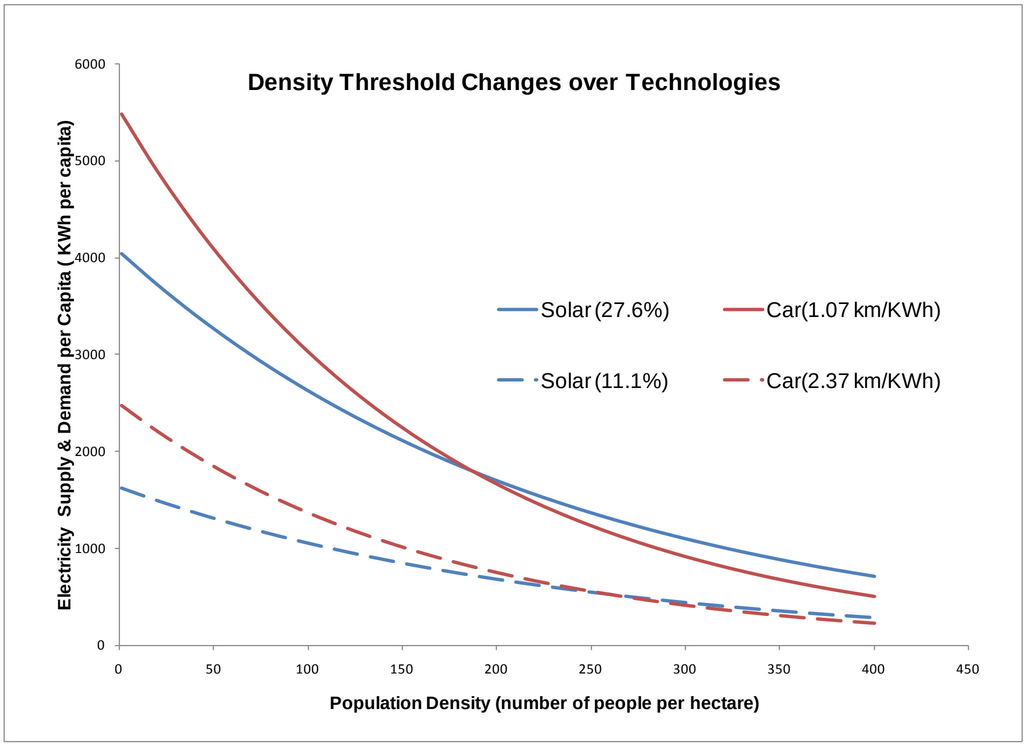
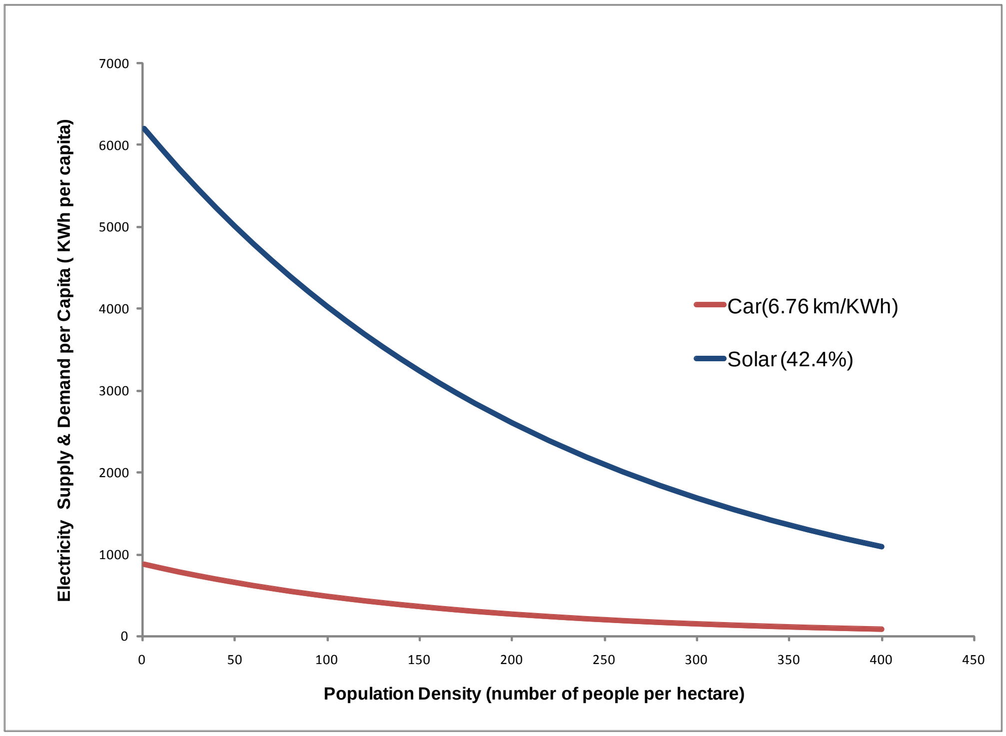
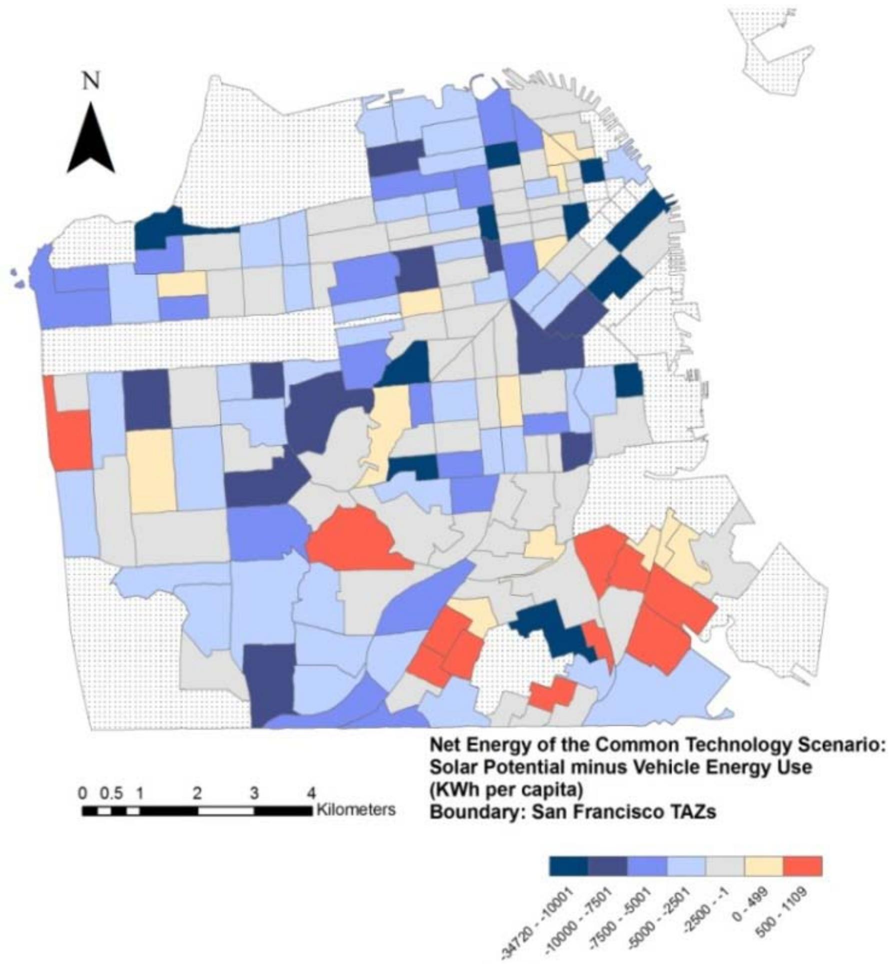


Figure 5.8 Vehicle energy demand versus rooftop solar energy supply per capita over population density at the best current technology scenario



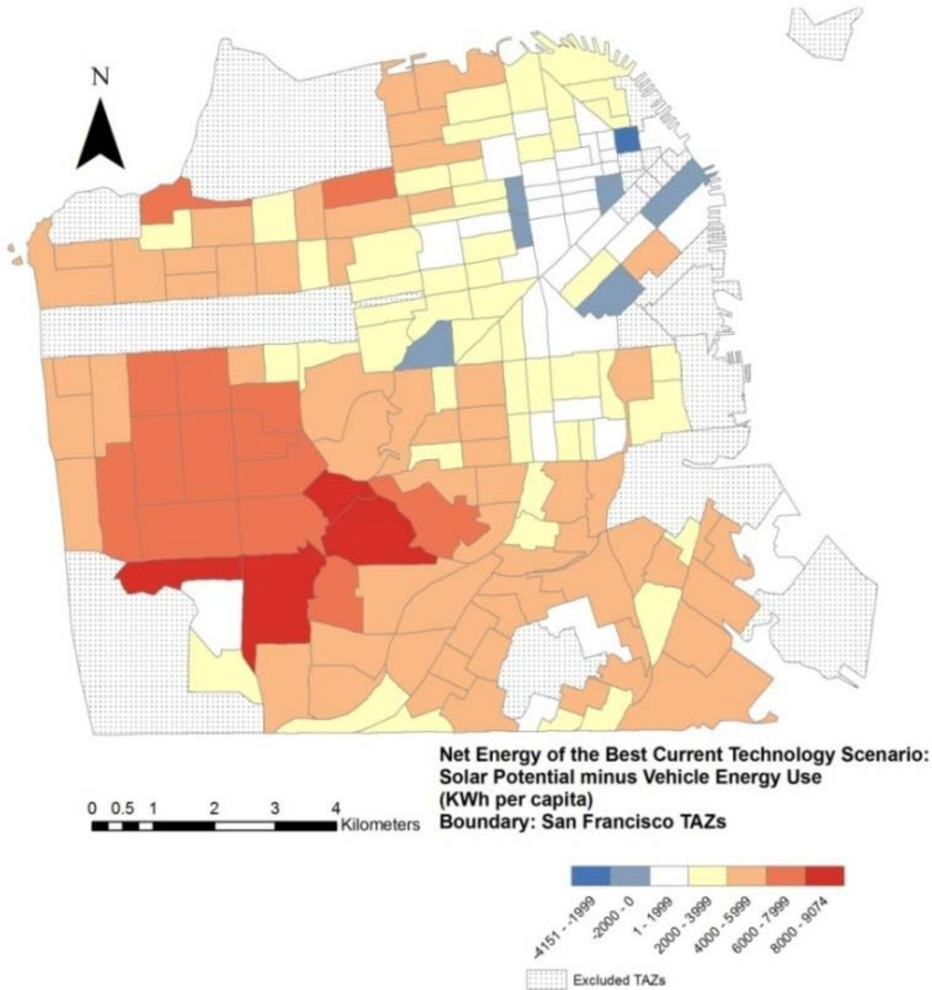
Using the projected trends of vehicle energy demand and solar energy supply, I geographically estimated the net energy (on-site solar energy potential minus vehicle energy use per capita) of each TAZ. Figure 5.9 and 5.10 shows the spatial patterns of the common technology combination (1.07 km/kWh vehicle efficiency and 11.1% solar panel efficiency) and the best current technology combination (6.76 km/kWh vehicle efficiency and 42.4 % solar panel efficiency). When assuming the common technologies of today (Figure 5.9) most TAZs show the negative net energy, except a few TAZs that have low population densities or extremely low vehicle uses. For the most part, the best current technology scenario (Figure 5.10) shows the opposite result, although it has a clearer spatial pattern.

Figure 5.9 The San Francisco map of the net energy value: the common technology scenario of today (1.07 km/kWh vehicle efficiency and 11.1% solar panel efficiency)



*Net energy value = on-site solar energy potential - vehicle energy use per capita

Figure 5.10 The San Francisco map of the net energy value: the best current technology scenario (6.76 km/kWh vehicle efficiency and 42.4 % solar panel efficiency)



*Net energy value = on-site solar energy potential - vehicle energy use per capita

5.5 Conclusion and Discussion

This study measured the trade-off between vehicle energy use and rooftop solar potential per person over a range of population density. VKT per capita and available rooftop per capita were two key variables that are directly related to vehicle energy use and rooftop solar energy potential. Using the 2000 Bay Area Travel Survey data, this study used network analysis to calculate realistic estimates of the average VKT per person for each TAZ in San Francisco. A three-dimensional urban surface model derived from LiDAR helped us assess the rooftop solar potentials of the real-world environment.

The results show that the density threshold, which reduces personal vehicle energy use while not compromising rooftop solar potentials, changes as vehicle and solar technologies improve and different combinations of them become available. Higher densities are shown to have a negative effect on both VKT and rooftop areas per person. As observed in the trends of VKT and available rooftop areas, both vehicle energy use and solar energy generation per capita also decreased as population density increased. Given the combination of current technologies (an average gasoline-based passenger vehicle and 11.1% for solar PV efficiency), the results reveal that solar energy generated on the rooftop PVs could not supply the energy for vehicle travel, especially in sprawl environments. In a transition stage where advanced vehicle and solar technologies become widely used, a density threshold change is mapped based on the different combinations of technologies. Finally, when assuming that the most advanced technologies dominate the market (electric cars and 42.4% efficiency of solar PV efficiency), the electricity generated by solar collectors exceeds the supply of electricity that one person consumes using electric vehicles across all ranges of population density.

This study provides an insight of how city planners can respond to technological development and policy shifts in energy fields. Specifically, this method can enable planners to define a density threshold and to set density standards for sustainable development as energy-efficient electric vehicles and on-site solar generation become more efficient and popular. Municipalities around the world are developing their short to long term energy efficiency strategies and climate change policies. The lack of quantified evidence has been a major barrier. Given this urgent need, our approach shows how much GHG emissions can be reduced by adjusting the physical environment (e.g. density) and by adopting new technologies. The findings support the development of new guidelines for municipal climate action plans as they attempt to solve two conflicting goals —maximizing on-site solar energy generation and to minimize vehicle energy use— in order to reduce net-energy use and associated net GHG emissions.

Although this method is universally applicable, I caution planners when using of our generalized results. Future research should investigate more variations in urban form and expand to include multiple cities. It should also investigate other density metrics such as: household density, floor area ratio, or population density per developed area. Lastly, the use of the comprehensive methods such as cost-benefit analysis (e.g. including life-cycle costs of vehicles or solar devices, the costs for construction and maintenance of infrastructure, electricity loss through transmission, farm land loss and the urban heat island effect) may contribute to understanding urban sustainability as a system. This study provides a foundation for future research employing different methods with larger samples encompassing diverse cases.

VI. Conclusion

6.1 Summary of Key Findings

This section serves as a summary of the key findings presented in Chapter III, IV and V. Under the notion of zero-net energy, each chapter represented a case study that examines the impact of urban form on energy demand and supply and their trade-offs in cities. In Chapter III, I started by exploring the demand side of zero net energy neighborhoods. I created a data rich model to assess the impact of urban form on space-cooling energy use in Sacramento. I extracted urban form variables such as density, street orientation and vegetation settings from GIS and LiDAR data and included them in a multivariate analysis along with other predictors. In Chapter IV, I moved to the supply of on-site green energy and investigated the effect of urban form on on-site solar energy generation. Among the many possible urban form variables, I focused on quantifying the effect of trees on residential rooftop solar potential and assessing the spatial pattern of their impacts on a citywide scale in San Francisco. In Chapter V, I incorporate vehicle energy use in the definition of ZNE neighborhoods and demonstrate trade-offs between on-site solar energy generation and vehicle energy use over urban density in San Francisco. The following sections summarize the results of these three studies.

(1) The Impacts of Urban Form on Space-cooling Energy Use

Controlling for occupant behavior, demographic and socioeconomic status and property condition, the statistical outputs of the final regression model reveal that urban forms have significant impacts on space-cooling energy use in Sacramento. Among the variables that represent urban forms, higher population density, east-west street orientation, higher green space density within a 100ft radius and a higher sum of tree heights on the east, south and west sides of houses appeared to have statistically significant effects on reducing summer cooling energy use. These findings validate many of the traditional energy saving urban design guidelines that had been developed in the 1960s through early 1980s (Hammond et al. 1981; Jaffe and Erley 1979; Knowles 1981; McClenon and Robinette 1977; McPherson 1984; Olgyay 1963; Thayer 1981). Although the effects of urban forms may be seen trivial compared to other contributors like occupant behavior, the findings of this study support that optimized community layout and vegetation planning would have a significant contribution to reducing space-conditioning energy use of a macro-scale environment.

The effects of street orientation and vegetation settings appear to be the most interesting and important. The results proved that east-west orientation, which has been reported as the most desirable orientation in urban design guidelines, is likely to reduce summer cooling electricity use in Sacramento compared to other street orientations. Evaluating the effect of street orientation on space-conditioning energy use is one of the unique contributions of the research in that no research has tested this effect using empirical energy use data. Assessing the effect of trees in each direction from a house also confirmed the results from previous literature (Donovan and Butry 2009; Hildebrandt and Sarkovich 1998; Simpson 2002). Using 3D information derived from LiDAR data, this study also proved that the heights of trees planted with east, south and west configurations contributed to reducing space-cooling energy use. In particular, trees planted west of a house showed the most statistically significant effects compared to those of trees planted in other directions. Furthermore, trees planted to the west of a house showed about two times greater effect on reducing summer cooling energy use than those planted to the east of a house and had a 1.8 times greater energy saving effect than those planted to the south of a house.

As for the effects of other predictors, baseline energy use is the single dominant factor that explains most of the variance in the response variable. When using common sense, it is not surprising that an occupant's daily energy use pattern is likely to directly affect their energy use pattern for cooling. Although the effects on cooling energy use are not as large as occupant behavior, some variables of socioeconomic status and property conditions also showed statistically significant associations with summer cooling energy use. Higher education attainment level and homeownership are significantly associated with less use of summer cooling electricity. I suppose that occupants with higher education levels are more likely to have access to environmental education and the opportunity to save energy. Homeowners appeared to save more cooling energy because they are likely to have more control in weatherizing their property in comparison to tenants. These efforts in weatherization are missing from our model and I expected that homeownership partially represented the possibilities for weatherizing properties. Houses built since 1984 (versus houses built before 1983), wooden roofs (versus asphalt composition shingles), smaller total floor areas, housing types with half-plex or planned unit developments (versus single family subdivisions) also appeared to reduce summer cooling electricity use. These results are comparable to previous literature where the adaptation of building codes, wooden roofs, smaller house sizes and attached housing units contributed to less space-conditioning energy consumption. Finally, a parcel with a pool is likely to use less summer cooling energy use compared to one without a pool after controlling for other variables. I suppose that swimming in the pool may serve as an alternative to using air conditioning at home. Since the water body density within a100ft radius shows no significant effects on cooling energy use, the evaporative cooling effects of pools did not appear to be statistically significant.

(2) The Impacts of Trees on Rooftop Solar Potential

Overall, the annual insolation on residential rooftops per area in San Francisco shows a wide range from 34.4 kWh/m^2/year to1348.4 kWh/m^2/year. I demonstrate a large variation of rooftop insolation across the city landscape through the use of maps. I find that the highest insolation levels are shown in the western and southern parts that consisted of homes with uniform building heights and high building coverage. In contrast, the central and the northwestern parts of San Francisco show a lower insolation potential. In particular, the Northwestern part (i.e. Downtown and Financial Districts) shows extremely low values due to the shade from neighboring skyscrapers with various heights. I also illustrate the impact of trees on the insolation of each residential rooftop across the city. The impact of trees on rooftop insolation also shows a wide range from 0 to 60%. Most locations that represented the impacts of trees on rooftop insolation appeared to be clustered on the central hill areas.

The statistical outputs of multiple regression models shows what attributes of trees reduce rooftop insolation. All predictors that are included in the model – tree density, average tree heights and variance of tree heights – shows statistically significant effects. A neighborhood with a higher tree density, higher average tree heights and a higher variance of tree heights is likely to have more reduction in its average rooftop insolation. Tree heights appeared to have a greater impact on rooftop insolation than tree density. In other words, although one neighborhood has a higher number of trees than another, the average reduced isolation on rooftops could be smaller if its average tree height is smaller than the other. In addition to the effect of the average tree heights, the variance of tree heights also appears to show the largest effect. It indicates that given two neighborhoods that have the same average tree heights, rooftop isolation decreases more in a neighborhood with a higher variance of tree heights.

With maps, I demonstrate that the tree density of neighborhoods is generally associated with a reduced insolation of the residential rooftops. Neighborhoods with a higher tree density (more than 20 trees per hectare), including the Inner Sunset, Twin Peaks and West of Twin Peaks, contain the most rooftop locations where the trees' impact is more than 20%. I find that the average and variance of tree heights add more details when explaining the spatial variance of the trees' impacts. Twin Peaks and the Inner Sunset,where the highest average tree heights and the height variance of trees are shown, include the most rooftop locations that are affected by trees.

(3) Trade-offs between On-site Solar Energy Generation and Vehicle Energy Use over Density

The results showed that VKT per capita and available rooftop per capita are two key variables that are directly related to vehicle energy use and rooftop solar energy potential. Higher densities appeared to have a negative effect on both VKT and rooftop areas per person. As observed in the trends of VKT and available rooftop areas, both vehicle energy use and solar energy generation per capita also decrease as population density increased.

The density threshold that allows personal vehicle energy use becomes smaller than rooftop solar potential, changes as vehicle and solar technologies improve and different combinations of them become available. Given the combination of current technologies (1.07 km/kWh efficiency for an average gasoline-based passenger vehicle and 11.1% for solar PV efficiency), this study reveals that solar energy generated on the rooftop PVs cannot supply the energy for vehicle travel, especially in sprawl environments. In a transition stage where advanced vehicle and solar technologies become widely used, the density threshold changes based on the different combinations of technologies. Finally, when assuming that all people drive electric cars and put the most efficient solar PVs on their rooftops (6.76 km/kWh efficiency of electric cars and 42.4% efficiency of solar multi-junction concentrators), the electricity generated by solar collectors exceeds the supply of electricity that one person consumes using electric vehicles across all ranges of population density.

6.2 Significance of Research and Policy Implication

First of all, by including a wide range of urban form variables, this research is the first comprehensive validation of many of the early theoretical works on climate responsive urban design and on-site solar energy guidelines in the 1960s through early 1980s. Although these principles have existed for several decades, a comprehensive assessment of the effects of desirable urban forms on energy demand and supply in cities has been extremely challenging due to lack of very large and rich data sets and computational capability. Using advanced spatial modeling with various 2D and 3D spatial data, I successfully test the association between different types of urban forms, energy demand and supply on a citywide scale. Most of the results confirm that traditional urban design guidelines are effective, arguing that the implementation of such guidelines are important in moving toward energy self-sufficient cities. This research demonstrates how much energy can be reduced or how much energy can be generated in cities by adjusting urban forms and by adopting new technologies.

The findings of this dissertation have important implications for research and practice on building energy efficient neighborhoods. First of all, I suggest that more energy related incentives and regulations are imperative not only on a single building scale but also for its neighboring environment on a community scale. The research findings support that rezoning for more attached housing with a higher density and more green space that maximizes east-west street orientation is warranted. In addition, regulating floor area ratios and lot coverage for solar access and incentives for appropriate tree planting can be effective tools for encouraging energy efficient neighborhoods.

Using this approach to spatially assess the impact of trees on rooftop insolation identifies the locations that will have potential solar access violations. California's Solar Right Act, Solar Shade Control Act and Public Resources Code (25982) states the notion of "solar easement"—the right of receiving sunlight across adjacent properties for use by any solar collector. Given this current regulation, it is imperative to map the locations that will have solar access violations in order to manage potential conflicts between stakeholders including PV owners and tree owners. The results can also be linked to municipal tree management programs. In the locations with high solar PV potential, municipalities can encourage home owners to manage their tree heights or to plant trees in optimal locations where trees will not conflict with rooftop PVs of their own or those of neighboring properties; and where they would also maximize cooling and/or heating effects.

Finally, this study provides an insight into how city planners can respond to technological development and policy shifts in energy related areas. Specifically, the method used in Chapter V can enable planners to define a density threshold that maximizes net energy, and to set density standards for sustainable development as energy-efficient electric vehicles and on-site solar generation become more efficient and popular. Municipalities around the world are developing their short to long term energy efficiency strategies and climate change policies. The lack of quantified evidence has been a major barrier. Given this urgent need, this approach demonstrates how much GHG emissions can be reduced by adjusting the physical environment (e.g. density) and by adopting new technologies. The findings of Chapter V support the development of new guidelines for municipal climate action plans as they attempt to solve two conflicting goals — maximizing on-site solar energy generation and minimizing vehicle energy use— in order to reduce net-energy use and associated net GHG emissions.

6.3 Limitations and Future Research

This study makes significant contributions to academia and provides valuable implications to planning practices, however there are limitations of the current approach and I suggest new directions for future research.

For a more coherent understanding of energy demand and the supply side of a city, it would have been ideal if I conducted three studies for the same study site that contains a wide spectrum of urban form types. For example, comparing the impacts of trees on rooftop PV potential ("active solar") versus the cooling impacts of tree shade ("passive solar") on the same site would contribute to a more comprehensive understanding of the benefits and the costs of trees in the residential energy sector. However, in order to build a data rich environment for each research question, this dissertation had to choose two study sites—Sacramento and San Francisco - and it still lacks some types of urban forms. For example, the study site in Sacramento did not provide sufficient cases of multi-family housing—most houses are single family detached houses.

As for assessing the impact of trees, higher temporal resolution (the daily or seasonal changes of the impact) will provide more detailed implications for maximizing rooftop solar energy generation. As for evaluating the trade-off between on-site solar energy generation and vehicle energy use over density, future studies can investigate the effects of more detailed density metrics such as: household density, floor area ratio, or population density per developed area. Although our method is universally applicable, I caution planners in the use of our generalized results. Future research should investigate more variations of urban forms, their trade-offs at a particular site, and expand to include multiple cities.

Furthermore, I suggest that future research put more effort into including key variables that predict space-conditioning energy use. Even though I included a number of relevant variables, the current statistical model still lacks significant determinants that may have strongly affected summer cooling energy use. For example, the inclusion of information with regards to glazing ratios, the energy efficiency of A/C systems and the insulation of walls, roofs and windows would significantly improve the explanatory power of the model. This additional information would require a significant amount of time and effort to collect these types of data through field surveys. However, in future studies, inclusion of these variables will be rewarding as a more concrete empirical model can be realized. While I select variables based on a confirmatory approach, future studies can use an exploratory approach and check possible interactions between predictors. Furthermore, investigating the association between urban forms and winter heating energy use will be a valuable addition in order to assess potential seasonal trade-offs in cooling and heating energy savings.

Although the 3D model developed here significantly improves the more traditional methods, I should note that the model contains some error due to data processing and data quality. I believe that more rigorous analysis on urban form extractions, especially for vegetation shapes and volumes, will contribute toward a better testing of the impact of vegetation. In chapter III, the sum of tree heights within a 30ft buffer zone for all configurations, reveals no statistical significance. This result may stem from the limitation of our current methods. For example, treetops, especially trees with large crowns, may not be detected in the 30ft buffer zone, although most of the volume of the crown is within the 30ft buffer zone from the house. The advancement of tree volume extraction would overcome this kind of problem. In Chapter IV, I assume that errors might stem from the quality of the data that I obtained from San Francisco. The Tree information (such as: number of trees and tree heights) may have errors as LiDAR may not fully detect the entire tree population. Since the data was generated through an automated process, the process might detect taller trees with distinctive shapes better than smaller ones with less distinctive forms. The method introduced here does a better job of capturing the impact of surrounding trees rather than the ones whose crowns cover the roofs.

Finally, the use of comprehensive methods such as cost-benefit analysis, including the life-cycle costs of vehicles, solar devices, weatherization and tree planting, the costs for construction and maintenance of different types of urban forms and electricity loss through transmission versus on-site energy supply systems (e.g. battery), may contribute to understanding urban sustainability as a system. This dissertation provides a foundation for future research employing different methods with larger samples encompassing diverse cases.

References

Aggarwal, R. 2006. Energy design strategies for city-centers: An evaluation. Paper presented at *the 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland*, September 6–8.

Akbari,H. 2002. Shade trees reduce building energy use and CO_2 emissions from power plants. *Environmental Pollution* 116: S119–S126.

Akbari, H., D. M. Kurn, S. E. Bretz, and J. W. Hanford. 1997. Peak power and cooling energy savings of shade trees. *Energy and Buildings* 25(2): 139–148.

Akbari, H. and H. Taha. 1992. The impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities. *Energy (Oxford)* 17(2): 141–149.

Akbari, H., M. Pomerantz, and H. Taha. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70(3): 295–310.

Ali-Toudert, F., and H. Mayer. 2006. Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment* 41(2):94–108.

Anders, S., K. Grigsby, and C. A.Kuduk.2007.California's Solar Rights Act: a review of the statues and relevant cases. Energy Policy Initiatives Center, University of San Diego School of Law. Retrieved from www.sandiego.edu/epic/publications/documents/070123_RightsActPaperFINAL.pdf

Arboit, M., A. Diblasi, J. C. Fernández Llano, and C. de Rosa. 2008. Assessing the solar potential of low-density urban environments in Andean cities with desert climates: The case of the city of Mendoza, in Argentina. *Renewable Energy* 33(8):1733–1748.

Arnfield, A. J. 1990. Street design and urban canyon solar access. *Energy and Buildings* 14 (2):117–131.

Baker, N., and K. Steemers. 2000. *Energy and Environment in Architecture: A Technical Design Guide*. London and New York: Taylor & Francis.

Beatley, T. 2007. Envisioning solar cities: Urban futures powered by sustainable energy. *Journal of Urban Technology*, 14(2): 31–46.

BRE. 1975. *Energy Conservation: A Study of Energy Consumption in Buildings and Means of Saving Energy in Housing*. CP-56. Garston, Watford, Herts: Building Research Establishment.

Brown, G. Z. 1985. *Sun, Wind, and Light: Architectural Design Strategies*. New York, Chichester, Brisbane, Toronto, Singapore: John Wiley & Sons, INC

California Public Utility Commission. 2008. California Long Term Energy Efficiency Strategic Plan. Retrieved from http://www.cpuc.ca.gov/NR/rdonlyres/70EC7B35-48DD-4FA3-9DD6-BC231BD458E9/0/EESP_ExecutiveSummary.pdf

Capeluto, I. and G.E. Shavivi.1997.Modeling the urban grids and fabric with solar rights considerations. *Solar World Congress*, ISES International Energy Society, Korea

Carneiro, C., E. Morello, C. Ratti, and F.Golay.2008. Solar radiation over the urban texture: LIDAR data and image processing techniques for environmental analysis at city scale.InZlatanova, S. & Lee, J (Eds.). *Lectures notes in geoinformation and cartography: 3d Geo-Information Sciences* (pp.319–340), Verlag Berlin Heidelberg, Springer.

Center for Landscape Architectural Education and Research. 1978. *Options for Passive Energy Conservation in Site Design*. Prepared for U.S. Department of Energy.

Cervero, R. 1996. Mixed land-uses and commuting: Evidence from the American Housing Survey. *Transportation Research Part A: Policy and Practice* 30(5): 361–377.

Cervero, R.and K.Kockelman.1997. Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D: Transport and Environment* 2(3): 199–219.

Chatman, D.G.2008.Deconstructing development density: Quality, quantity and price effects on household non-work travel. *Transportation Research Part A: Policy and Practice*, 42(7):1008–1030.

Chatterjee, S., and A. S. Hadi. 2006. *Regression Analysis by Example*. New York, Chichester, Brisbane, Toronto, Singapore: John Wiley and Sons.

Cheng, V., K. Steemers, M. Montavon, and R. Compagnon. 2006. Urban form, density and solar potential. Paper presented at *the 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland*, September6–8.

City and County of San Francisco. 2008. San Francisco Enterprise GIS Program. Retrieved from http://gispub02.sfgov.org/

City of Berkeley. 2008. Berkeley FIRST: Financing Initiative for Renewable and Solar Technology. Office of Energy and Sustainable Development. Retrieved from http://www.ci.berkeley.ca.us/contentdisplay.aspx?id=26580

City of Sacramento. 2012. About the City of Sacramento. Retrieved from http://www.cityofsacramento.org/about_the_city.htm

Clark, K. E., and D. Berry. 1995. House characteristics and the effectiveness of energy conservation measures. *Journal of the American Planning Association* 61(3): 386–395.

Compagnon, R. 2004. Solar and daylight availability in the urban fabric. *Energy & Buildings* 36 (4): 321–328.

Costa, D. L. and M. E.Kahn.2010. *Why Has California's Residential Electricity Consumption Been So Flat since the 1980s?: A Microeconometric Approach* (NBER Working Paper Series). National Bureau of Economic Research. Retrieved from http://www.nber.org/papers/w15978

Crawford, C. 2009. Lidar Solutions in ArcGIS_part3: Data Area Delineation from Lidar Points. *ArcGIS Resouce Center*. ArcGIS Blog. Retrieved from http://blogs.esri.com/esri/arcgis/2009/02/13/lidar-solutions-in-arcgis_part3-data-area-delineation-from-lidar-points/

DeWalle, D. R.and G. M. Heisler. 1983. Windbreak effects on air infiltration and space heating in a mobile home. *Energy and Buildings* 5(4): 279–288.

DeWalle, D. R., G. M. Heisler, and R. E. Jacobs. 1983. Forest home sites influence heating and cooling energy. *Journal of Forestry* 81(2): 84–88.

Diamond, S. C., C. C. Cappiello, and B. D. Hunn. 1986. *DOE-2 Verification Project. Phase I. Final Report*. Los Alamos National Laboratory.

Donovan, G. H., and D. T. Butry. 2009. The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy and Buildings* 41(6): 662–668.

Edminster, A. V. 2009. *Energy Free: Homes for a Small Planet*. San Rafael, CA: Green Building Press.

Energy Information Administration. 2008. Annual Energy Review 2008. Retrieved from http://www.eia.doe.gov/emeu/aer/consump.html.

Erley, D. and M. Jaffe. 1979. *Site Planning for Solar Access: A Guidebook for Residential Developers and Site Planners*. Prepared for U.S. Department of Housing and Urban Development.

ESRI. 2011a. ArcGIS Desktop 9.3 Help. *Kernel Density*. Retrieved from http://webhelp.esri.com/arcgiSDEsktop/9.3/index.cfm?TopicName=Kernel_Density

ESRI. 2011b. *The American Community Survey*. An ESRI White Paper. Retrieved from http://www.esri.com/library/whitepapers/pdfs/the-american-community-survey.pdf

Ewing, R.2001. Travel and the built environment: a synthesis. *Transportation Research Record: Journal of the Transportation Research Board* 1780: 87–114.

Ewing, R.,K. Bartholomew, S. Winkelman, J. Walters, and D. Chen. 2008. *Growing cooler: evidence on urban development and climate change*. Washington, DC: Urban Land Institute.

Ewing, R. andR. Cervero. 2010. Travel and the built environment. *Journal of the American Planning Association* 76 (3): 265–294.

Ewing, R.,M. Deanna, and S. Li.1996.Land use impacts on trip generation rates. *Transportation Research Record: Journal of the Transportation Research Board* 1518, 1–6.

Ewing, R., and F. Rong. 2008. The impact of urban form on US residential energy use. *Housing Policy Debate* 19 (1): 1–30.

Gadsden, S.,M. Rylatt, and K. Lomas.2003. Putting solar energy on the urban map: a new GIS-based approach for dwellings. *Solar Energy* 74(5): 397–407.

Gadsden, S., M. Rylatt, K. Lomas, and D. Robinson.2003. Predicting the urban solar fraction: a methodology for energy advisers and planners based on GIS. Energy and Buildings, 35(1): 37–48.

Givoni, B. 1998.*Climate Considerations in Building and Urban Design*. New York: Wiley & Sons.

Golany, G. S. 1996. Urban design morphology and thermal performance. *Atmospheric Environment* 30 (3): 455–465.

Goulding, J. R., J. O. Lewis, and T. C. Steemers. 1991. *Energy in Architecture: The European Passive Solar Handbook*, London: BT Batsford Ltd.

Hammond, J., J. Zanetto, and C. Adams. 1981. *Planning Solar Neighborhoods*. Prepared for the California Energy Commission.

Heisler, G. M.1986a. Effects of individual trees on the solar radiation climate of small buildings. *Urban Ecology* 9 (3-4):337–359.

———.1986b. Energy savings with trees. *Journal of Arboriculture* 12 (5): 113-125.

Hildebrandt, E. W., and M. Sarkovich. 1998. Assessing the cost-effectiveness of SMUD's shade tree program. *Atmospheric Environment* 32 (1): 85–94.

Hirst, ., R. Goeltz, and J. Carney. 1982. Residential energy use : Analysis of disaggregate data. *Energy Economics* 4 (2): 74–82.

Hofierka, J., and J. Kanuk, 2009.Assessment of photovoltaic potential in urban areas using open-source solar radiation tools. *Renewable Energy*, 34(10): 2206–2214.

Holden, E., and I. T. Norland. 2005. Three challenges for the compact city as a sustainable urban form: household consumption of energy and transport in eight residential areas in the greater Oslo region. *Urban Studies* 42 (12): 2145– 2166.

Holtz, M. J. 1990. *Design Guidelines: An International Summary*. Washington, DC: International Energy Agency: Solar Heating and Cooling Program.

Holtzclaw, J. 1994. *Using residential patterns and transit to decrease auto dependence and costs.* San Francisco, CA: Natural Resources Defense Council. Retrieved from http://docs.nrdc.org/smartGrowth/files/sma_09121401a.pdf

Holtzclaw, J.,R. Clear, H. Dittmar, D. Goldstein, and P. Haas. 2002. Location efficiency: Neighborhood and socio-economic characteristics determine auto ownership and use - studies in Chicago, Los Angeles and San Francisco. *Transportation Planning and Technology* 25(1):1–27.

Hough, M. 1995. *Cities and Natural Process*. London and New York: Routledge.

Huang, J., H. Akbari, H. Taha, and A. H. Rosenfeld. 1987. The potential of vegetation in reducing summer cooling loads in residential buildings. *Journal of Applied Meteorology* 26 (9): 1103–1116.

Hui, Sam C. M. 2001. Low energy building design in high density urban cities. *Renewable energy* 24 (3-4):627–640.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate change 2007: the physical science basis,* summary for Policy makers. Retrieved from http://ipcc-wg1.ucar.edu/wg1/docs/WG1AR4_SPM_PlenaryApproved.pdf

Jaffe, M. and D. Erley. 1979. *Protecting Solar Access for Residential Development: A Guidebook for Planning Officials*. Prepared for U.S. Department of Housing and Urban Development.

Jensen, R. R., J. R. Boulton, and B. T. Harper. 2003.The relationship between urban leaf area and household energy usage in Terre Haute, Indiana, US. *Journal of Arboriculture* 29 (4): 226–230.

Johnson, G. D., W. P. Erickson, M. D. Strickland, M. F. Shepherd, D. A. Shepherd, and S.A. Sarappo,2002.Collision mortality of local and migrant birds at a large-scale wind-power development on Buffalo Ridge, Minnesota. Wildlife Society Bulletin, 879–887.

Jones, K., and D. Duncan.1995. Individuals and their ecologies: analysing the geography of chronic illness within a multilevel modelling framework. *Health & Place, 1*(1), 27–40. doi:10.1016/1353-8292(95)00004-6

Kahn, M. E. 2000. The environmental impact of suburbanization. *Journal of Policy Analysis and Management* 19 (4): 569-586.

Kaza, N. 2010.Understanding the spectrum of residential energy consumption: A quantile regression approach. *Energy Policy* 38(11): 6574–6585.

Kitamura, R.,T. Akiyama, T. Yamamoto, and T. Golob, 2001. Accessibility in a metropolis: Toward a better understanding of land use and travel. *Transportation Research Record: Journal of the Transportation Research Board* 1780: 64–75.

Knowles, R.L. 1974. *Energy and Form*. Cambridge, MA: MIT Press

———. 1981. *Sun Rhythm Form*. Cambridge and London: The MIT Press

———. 2003. The solar envelope: its meaning for energy and buildings. *Energy and Buildings* 35 (1): 15–25.

Knowles, R. L. and R. D. Berry. 1980. *Solar Envelope Concepts: Moderate Density Building Applications* . Solar Energy Information Data Bank.

Ko, Y., D. K. Schubert, and R. T. Hester. 2011. A conflict of greens: green development versus habitat preservation– the case of Incheon, South Korea. *Environment: Science & Policy for Sustainable Development*, 53(3): 3–17.

Krishan, A., N. Baker, S. Yannas, and S. Szokolay. 2001. *Climate Responsive Architecture: A Design Handbook for Energy Efficient Buildings*. New Delhi: Tata McGraw-Hill.

Kristl, Z., and A. Krainer. 2001. Energy evaluation of urban structure and dimensioning of building site using iso-shadow method. *Solar energy*, 70(1): 23–34.

Laband, D. N., and J. P. Sophocleus. 2009. An experimental analysis of the impact of tree shade on electricity consumption. *Arboriculture and Urban Forestry* 35(4): 197–202.

Lantsberg, A. 2005.*Sustainable Urban Energy Planning: A Roadmap for Research and Funding*. Prepared for California Energy Commission. Retrieved from http://www.energy.ca.gov/2005publications/CEC-500-2005-102/CEC-500-2005-102.PDF

Lariviere, I. and G. Lafrance. 1999. Modelling the electricity consumption of cities: effect of urban density. *Energy economics* 21(1): 53–66.

Láveme, R. J., and G. M. Lewis.1996. The effect of vegetation on residential energy use in Ann Arbor, Michigan. *Journal of Arboriculture*, 22(5): 234–243.

Lee, J. H. 2010. *Automated approaches for extracting individual tree level forest information using high spatial resolution remotely sensed data*. Doctoral Dissertation, University of California, Berkeley, Berkeley, CA.

Lee, J. H., G. S. Biging, P. Gong, and J. B. Fisher (In review).An Individual Tree-Based Automatic Registration of Aerial Images to Airborne LiDAR Data. *Photogrammetric Engineering and Remote Sensing*.

Levinson, R., H. Akbari, M. Pomerantz, and S. Gupta. 2009. Solar access of residential rooftops in four California cities. *Solar Energy*, 83(12): 2120–2135.

Littlefair, P. 1998. Passive solar urban design: ensuring the penetration of solar energy into the city. *Renewable and Sustainable Energy Reviews* 2(3): 303–326.

Littlefair, Paul., M. Santamouris, S. Alvarez, A. Dupagne, D. Hall, J. Teller, J.F. Coronel, and N. Papanikolaou. 2000. *Environmental Site Layout Planning Solar Access, Microclimate and Passive Cooling in Urban Areas*. London: CRC Ltd.

McClenon, C.and G. O. Robinette. 1977. *Landscape Planning for Energy Conservation*. Prepared for the Center for Landscape Architectural Education and Research. Reston, VA: Environmental Design Press.

McPherson, E. G., edit. 1984. *Energy-Conserving Site Design*. Washington D.C.: American Society of Landscape Architects.

McPherson, E. G., L. P. Herrington, and G. M. Heisler. 1988. Impacts of vegetation on residential heating and cooling. *Energy and Buildings* 12 (1): 41–51.

McPherson, E. G., D. Nowak, G. Heisler, S. Grimmond, C. Souch, R. Grant, and R. Rowntree. 1997. Quantifying urban forest structure, function, and value: The Chicago urban forest climate project. *Urban Ecosystems* 1(1): 49‒61.

McPherson, E. G. and R. A. Rowntree. 1993. Energy conservation potential of urban tree planting. *Journal of Arboriculture* 19:321‒321.

McPherson, E. G., and J. R. Simpson.2003. Potential energy savings in buildings by an urban tree planting programme in California. *Urban Forestry & Urban Greening*, 2(2), 73–86. doi:10.1078/1618-8667-00025

McPherson, E. G., J. R. Simpson, and M. Livingston. 1989. Effects of three landscape treatments on residential energy and water use in Tucson, Arizona. *Energy and Buildings* 13(2): 127‒138.

Meldem, R., and F.Winkelmann. 1998. Comparison of DOE-2 with temperature measurements in the Pala test houses. *Energy and Buildings* 27 (1):69–81.

Metropolitan Transportation Commission. 2011. *California Vehicle Miles Traveled per Capita*. Retrieved from http://www.mtc.ca.gov/maps_and_data/GIS/maps/monthly/January_2011_VMT_Per_Capita_California.pdf

Mindali, O.,A. Raveh, and I. Salomon.2004. Urban density and energy consumption: a new look at old statistics. *Transportation Research Part A* 38(2): 143–162.

Minne, A. 1988.*Energy Design Principles in Buildings*. Louvain-la-Neuve, Belgium: International Energy Agency: Solar Heating and Cooling Program.

Mitchell, G. 2005. Urban development, form and energy use in buildings: A review for the SOLUTIONS project. School of Geography and Institute for Transport Studies, University of Leeds. Retrieved from http://www.suburbansolutions.ac.uk/DocumentManager/secure0/Urban development, form and energy use in buildings.pdf

Moffat, A. S., and M. Schiler. 1981. *Landscape Design that Saves Energy*. New York, NY: William Morrow and Company.

Morello, E., and C. Ratti. 2009. Sunscapes: ‘Solar envelopes’ and the analysis of urban DEMs. *Computers, Environment and Urban Systems* 33 (1): 26–34.

Naess, P.,S. L. Sandberg, and P. G. Roe.1996.Energy use for transportation in 22 Nordic towns. *Housing, Theory and Society* 13(2): 79–97.

National Climate Data Center.2011. Climate of the World. NOAA Satellite and Information Service. Retrieved from http://www.ncdc.noaa.gov/oa/wdc/index.php?name=climateoftheworld

NBA Tectonics. 1988. *A Study of Passive Solar Housing Estate Layout.* Report S1126, Harwell, UK: Energy Technology Support Unit.

New York City Solar America City Partnership.(2011). New York City Solar Map. Retrieved from http://www.nycsolarmap.com/

Newman, P. G. and J. R. Kenworthy.1989. *Cities and Automobile Dependence: An International Sourcebook.* Aldershot, UK: Gower Publishing Company.

Newman, P., T. Beatley, and H. Boyer. 2009. *Resilient cities: responding to peak oil and climate change*. Washington, DC: Island Press.

Nguyen, H. T., and J. M. Pearce. 2010. Estimating potential photovoltaic yield with r.sun and the open source Geographical Resources Analysis Support System. *Solar Energy* 84(5): 831–843.

Olgyay, V. 1963.*Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton, NJ: Princeton University Press.

Ordenes, M., D.L. Marinoski, P. Braun, and R. Ruther. 2007. The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil, *Energy and Buildings* 39:629–642

Overmars, K. P. andP. H. Verburg.2006. Multilevel modelling of land use from field to village level in the Philippines. *Agricultural Systems*, *89*(2–3): 435–456.

Owens, S. E. 1986. *Energy, Planning, and Urban Form*. London: Pion Ltd.

Pandit, R., and D. N. Laband. 2010a. A hedonic analysis of the impact of tree shade on summertime residential energy consumption. *Arboriculture & Urban Forestry* 36(3): 73–80

Pandit, R., and D. N. Laband. 2010b. Energy savings from tree shade. *Ecological Economics* 69 (6): 1324–1329.

Paradis, M.A., G. Faucher, and D.N. Nguyen. 1983. Street orientation and energy consumption in residences. *ASHRAE Transactions* 89 (1A): 276–287.

Parker, J. H. 1983.Landscaping to reduce the energy used in cooling buildings. *Journal of Forestry* 81 (2): 82–105.

———. 1987. The Use of Shrubs in Energy Conservation Plantings. *Landscape Journal* 6: 132–139.

Parsons Brinckerhoff Quade and Douglas, Inc.1993. The pedestrian environment. Portland, OR: 1000 friends of Oregon. Retrieved from http://ntl.bts.gov/DOCS/tped.html

Parsons Brinckerhoff Quade and Douglas, Inc. 1994.*Building orientation - A supplement to the pedestrian environment.* Portland, OR: 1000 friends of Oregon. Retrieved from http://ntl.bts.gov/DOCS/bob.html

Pérez-Lombard, L., J. Ortiz, and C. Pout. 2008. A review on buildings energy consumption information. *Energy and Buildings* 40(3):394–398.

Pickrell, D.,and P. Schimek.1999. Growth in motor vehicle ownership and use: Evidence from the Nationwide Personal Transportation Survey. *Journal of Transportation and Statistics 2*(1), 1–17.

Rabe-Hesketh, S., and A. Skrondal.2008.*Multilevel and longitudinal modeling using Stata*. Stata Corp.

Randolph, J. 2008. Comment on Reid Ewing and Fang Rong's' the impact of urban form on U.S. residential energy use'. *Housing Policy Debate* 19(1): 45–52.

Ratti, C., N. Baker, and K. Steemers. 2005. Energy consumption and urban texture. *Energy & Buildings* 37 (7): 762–776.

Robinette, G. O. 1983. *Energy Efficient Site Design*. New York: Van Nostrand Reinhold Company.

Rosenfeld, A. H., H. Akbari, J. J. Romm, and M. Pomerantz. 1998. Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings* 28(1): 51–62.

Rudie, R. J., and R. S. Dewers. 1984. Effects of tree shade on home cooling requirements. *Journal of Arboriculture* 10(12): 320–322.

Rylatt, M., S. Gadsden, and K. Lomas.2003. Using GIS to estimate the replacement potential of solar energy for urban dwellings. *Environment and Planning B: Planning and Design* 30(1): 51–68.

Schimek, P. 1996. Household motor vehicle ownership and use: How much does residential density matter? *Transportation Research Record: Journal of the Transportation Research Board* 1552: 120–125.

Sharlin, N., and M. E. Hoffman. 1984. The urban complex as a factor in the air-temperature pattern in a Mediterranean coastal region. *Energy and Buildings* 7 (2): 149–158.

Simpson, J. R. 1998. Urban forest impacts on regional cooling and heating energy use: Sacramento County case study. *Journal of Arboriculture* 24: 201–214.

———. 2002. Improved estimates of tree-shade effects on residential energy use. *Energy and Buildings* 34 (10): 1067-1076.

Simpson, J. R, and E. G. McPherson. 1996. Potential of tree shade for reducing residential energy use in California. *Journal of Arboriculture* 22: 10–18.

Simpson, J. R. and E. G. McPherson. 1998. Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. *Atmospheric Environment* 32(1): 69–74.

Socolow, R. H. 1978a. The Twin Rivers Program on energy conservation in housing: highlights and conclusion. *Energy and Buildings* 1(3): 207–242.

———.1978b. *Saving Energy in the Home: Princeton's Experiments at Twin Rivers.* Cambridge, MA: Ballinger Publishing Company.

Staley, S. R. 2008. Missing the forest through the trees? Comment on Reid Ewing and Fang Rong's the impact of urban form on U.S. residential energy use'. *Housing Policy Debate* 19 (1): 31–43.

State of California. (2011). Go Solar California. Retrieved from http://www.gosolarcalifornia.org/about/index.php

Steemers, K. 2003. Energy and the city: density, buildings and transport. *Energy and Buildings* 35 (1): 3–14.

Šúri, M., and J. Hofierka.2004. A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments. Transactions in GIS, 8(2): 175–190.

T O'Brien, W., C. A. Kennedy, A.K. Athienitis, T. J. Kesik. 2010.The relationship between net energy use and the urban density of solar buildings. *Environment and Planning B: Planning and Design* 37(6): 1002 – 1021.

Thayer Jr, R. L., J. Zanetto, and B. T. Maeda. 1983. Modeling the effects of street trees on the performance of solar and conventional houses in Sacramento, California. *Landscape Journal* 2(2): 155–164.

Thayer, Jr., R. L. 1981. *Solar access:"It's the Law!"A Manual on California's Solar Access Laws for Planners, Designers, Developers, and Community Officials*. Environmental Quality Series. Davis, CA: Institute of Governmental Affairs; Institute of Ecology.

The AIA Research Corporation. 1978. *Regional guidelines for building passive energy conserving homes*. Prepared for the U.S. Department of Housing and Urban Development and the U.S. Department of Energy.

Tooke, T. R., N. C. Coops, J. A. Voogt, and M. J. Meitner. 2011. Tree structure influences on rooftop-received solar radiation. *Landscape and Urban Planning* 102(2):73–81.

Torcellini, P., S.Pless, M. Deru, and D. Crawley.2006. Zero energy buildings: a critical look at the definition. National Renewable Energy Laboratory, US Department of Energy. Retrieved from http://www.nrel. gov/docs/fy06osti/39833.pdf.

Tsoutsos, T., N. Frantzeskaki, and V. Gekas.2005. Environmental impacts from the solar energy technologies. Energy Policy, 33(3): 289–296.

U.S. Bureau of Transportation Statistics. 2011. National transportation statistics. Retrieved March 2, 2011, fromhttp://www.bts.gov/publications/national_transportation_statistics

U.S. Department of Energy and US Environmental Protection Agency. 2011. www.fueleconomy.gov. Retrieved from http://www.fueleconomy.gov/

U.S. Department of Energy. 2011. Tax Credits for Energy Efficiency. Retrieved from http://www.energysavers.gov/financial/70010.html

U.S. National Renewable Energy Laboratory.2011. *Best research-cell efficiencies*. Retrieved from http://en.wikipedia.org/wiki/File:PVeff(rev110408U).jpg

U.S. Census Bureau. 2012. *State and County Quickfacts: Sacramento, CA.* Retrieved from http://quickfacts.census.gov/qfd/states/06/0664000.html

Vardimon, R. 2011. Assessment of the potential for distributed photovoltaic electricity production in Israel. *Renewable Energy* 36(2): 591–594.

Wiginton, L. K., H. T. Nguyen, and J. M. Pearce. 2010. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. *Computers, Environment and Urban Systems*. 34(4): 345–357

Zegras, C. 2010. The built environment and motor vehicle ownership and use: evidence from Santiago de Chile. *Urban Studies* 47(8): 1793–1817.

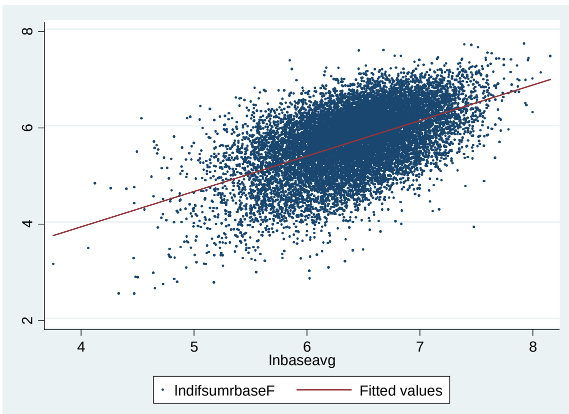
Zhou, B. B. and K. M. Kockelman. 2008. Self-selection in home choice: use of treatment effects in evaluating relationship between built environment and travel behavior. *Transportation Research Record: Journal of the Transportation Research Board* 2077: 54–61.

Appendix A. Model Diagnostics

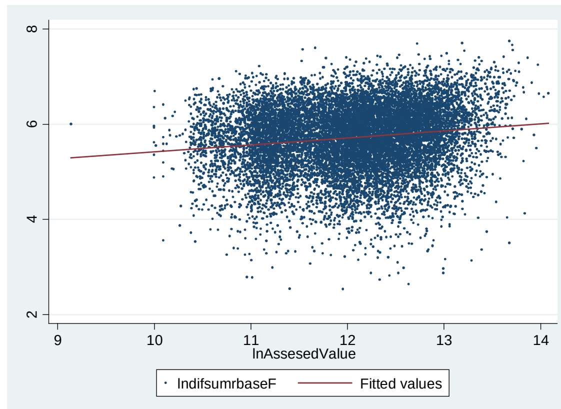
Chapter III

1. Scatterplots to check assumption of linearity for continuous predictor

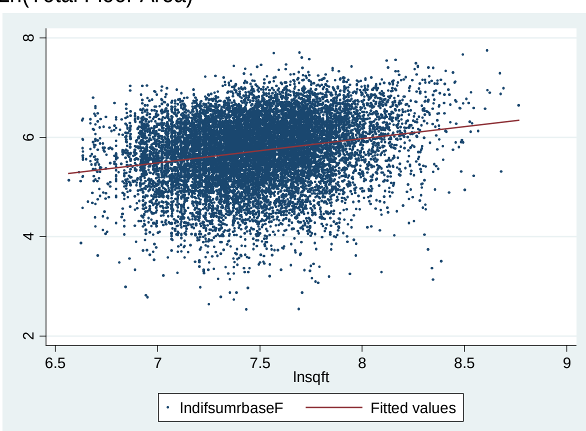
Ln(Baseline Energy Use)



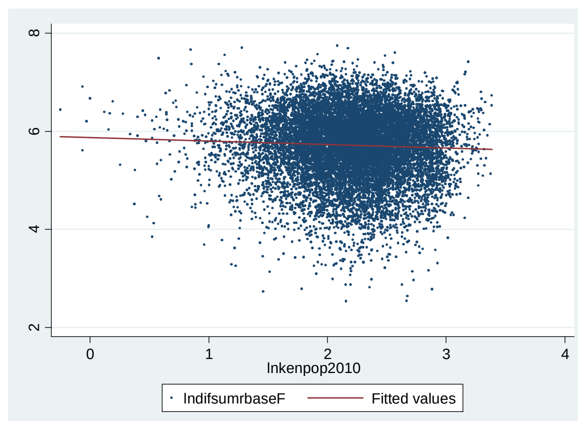
Ln(Property Assessed Value)



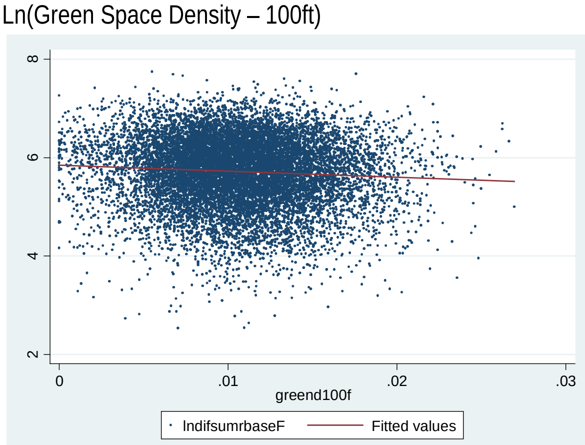
Ln(Total Floor Area)



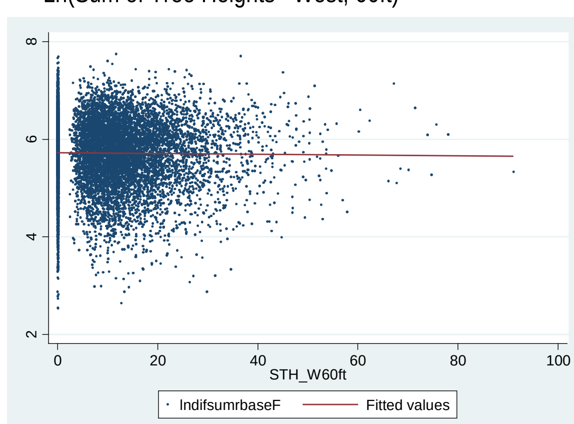
Ln(Population Density)



Ln(Green Space Density – 100ft)

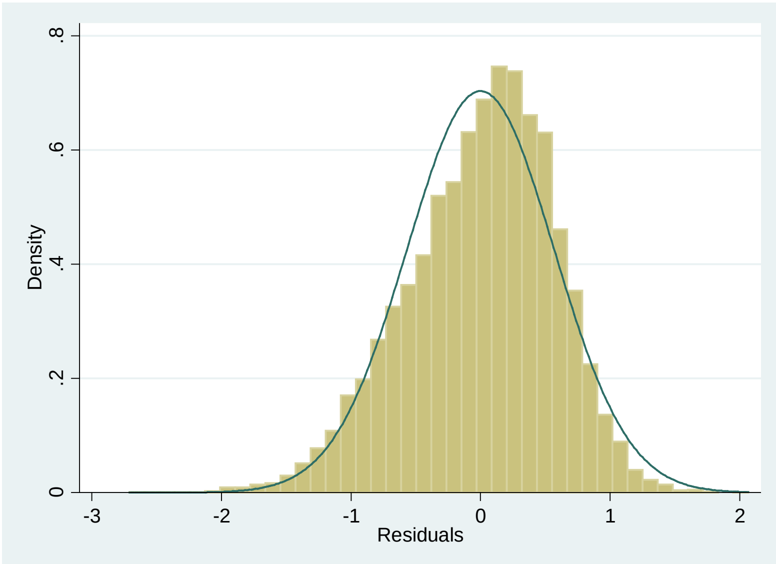


Ln(Sum of Tree Heights –West, 60ft)



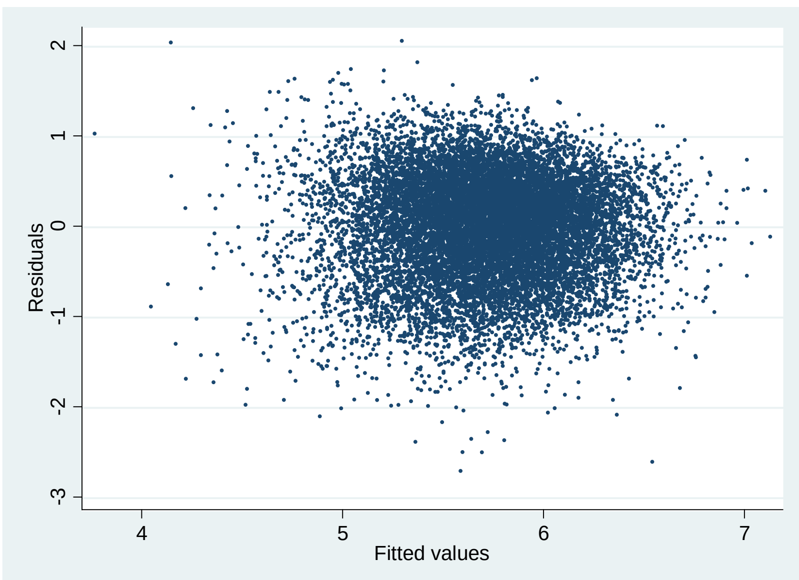
Ln(Baseline Energy Use), ln(Property Assessed Value), ln(Total Floor Area) and ln(Green Space Density – 100ft) show quite linear relationship with ln (Summer Cooling Energy Use). Ln(Population Density) and ln(Sum of Tree Heights –West, 60ft) show relatively weak linear relationships. The residuals are quite balanced along the fitted lines of each continuous predictor. It suggests that the linearity assumption for predictors appears to be generally satisfied.

2. Histogram of residuals to check assumption of normality of residuals



The histogram of the residuals appears to be approximately normal.

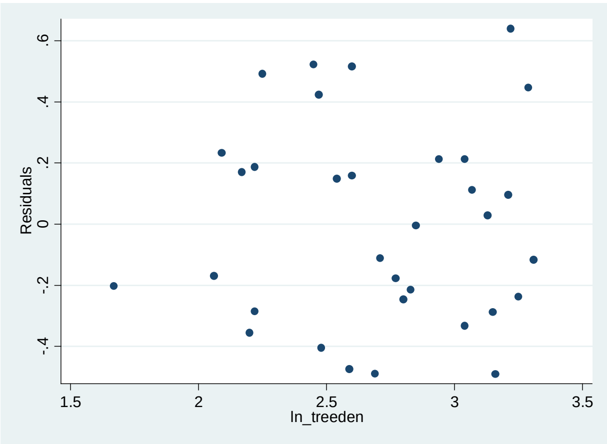
3. Scatterplot of residuals versus fitted values to check assumption of constant variance of residuals

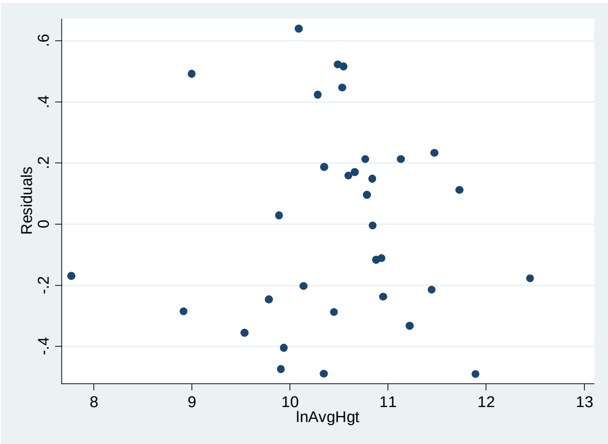


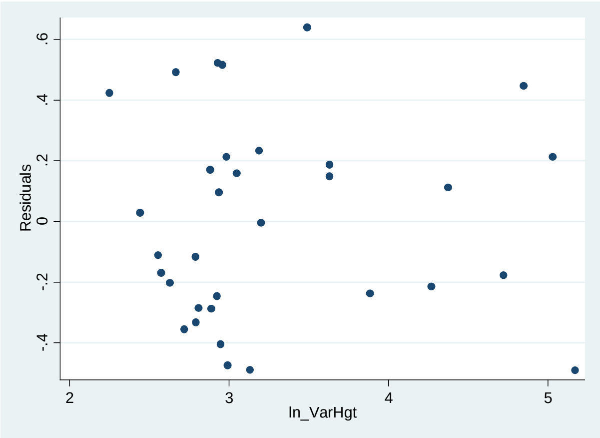
The scatter pattern shows that the variance appears not to be proportional to certain predictors.

Chapter IV.

1. Residual versus predictor plot to check assumption of Linearity for continuous predictor

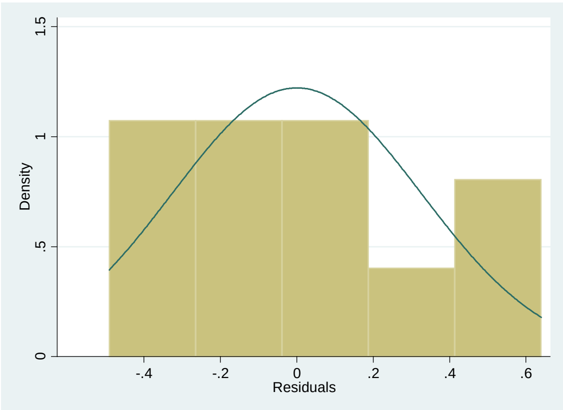






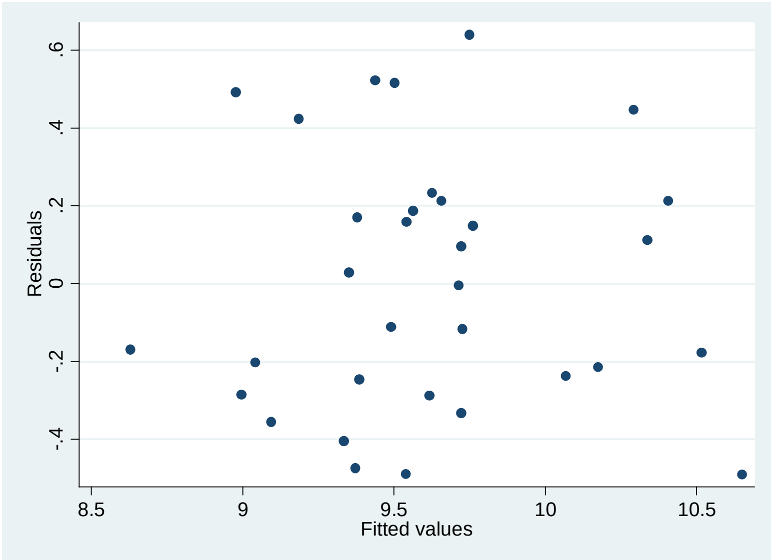
The mean residuals are about zero for each continuous predictor. It suggests that the linearity assumption for predictors appears to be generally satisfied.

2. Histogram of residuals to check assumption of normality of residuals



The histogram of the residuals appears not to be normal.

3. Scatterplot of residuals versus fitted values to check assumption of constant variance of residuals



The amount of scatter around the horizontal line appears to be constant.

Appendix B. Stata Commands

Chapter III.

```
*Descriptive Statistics of Continuous Variables
summarize difsummrbasef baseavg p_white r_diverse p_bach_hig p_over18
assessed_v  hmi_est sq_ft garage_sq kenpop2010 kendwuden greend100f greden500
waterd100f waterd500f sth_e30ft sth_s30ft sth_w30ft sth_n30ft sth_e60ft
sth_s60ft sth_w60ft sth_n60ft

*Distribution of Continuous Variables
histogram difsummrbasef, norm
histogram lndifsumrbasef, norm
histogram waterd100f, norm
histogram sth_w60ft, norm

*Frequency Chart for Categorical Variables
tabulate yrbuilt_3c
tabulate specific
tabulate detail
tabulate n_rm_cat
tabulate poolown
tabulate homeowner
tabulate roof_type
tabulate storit

*Boxplot for Categorical Variables
graph box lndifsumrbasef, over(yrbuilt_3c)
graph box lndifsumrbasef, over(n_stor_cat)
graph box lndifsumrbasef, over(homeowner)
graph box lndifsumbase, over(pool1)
graph box lndifsumrbasef, over(roof_type)
graph box lndifsumrbasef, over(storit)


*Checking ICC between Census Blocks
generate BlkID = substr(geoblkid, 9, 15)
destring BlkID, replace
xtreg lndifsumrb,  i(BlkID) mle

* Checking ICC between Census Tracts
generate TrkID = substr(geotrkid, 9, 4)
destring TrkID, replace
xtreg lndifsumrb,  i(TrkID) mle


* Full Model (Robust)
regress lndifsumrbasef lnbaseavg p_white r_diverse p_bach_hig p_over18
hmi_est lnassesedvalue homeowner built_b1960 built_a1983 n_stori_2 lnsqft
nrms_3_5 nrms_8_mr garage_sq_ lot_size twosfunits duplex halfplex nonsubdiv
plannedunitd poolown  rooftype2 rooftype3 lnkenpop2010 lnkendwuden nesw ns
nwse greend100f greden500 waterd100f waterd500f sth_e30ft sth_s30ft sth_w30ft
sth_n30ft sth_e60ft sth_s60ft sth_w60ft sth_n60ft, vce (robust)

*Checking Collinearity
vif
```

```
* Reduced Model using Stepwise Regression (Robust)
stepwise, lockterm pr(.4): regress lndifsumrbasef lnbaseavg p_white r_diverse
p_bach_hig p_over18  hmi_est lnassesedvalue homeowner (built_b1960
built_a1983) n_stori_2 lnsqft (nrms_3_5 nrms_8_mr) garage_sq_ lot_size
(twosfunits duplex halfplex nonsubdiv plannedunitd) poolown  (rooftype2
rooftype3) lnkenpop2010 lnkendwuden (nesw ns nwse)  greend100f greden500
waterd100f waterd500f (sth_e30ft sth_s30ft sth_w30ft sth_n30ft) (sth_e60ft
sth_s60ft sth_w60ft sth_n60ft), vce(robust)

*Checking Collinearity
vif


*Model 1 (Robust)
regress lndifsumrbasef lnbaseavg, vce(robust)

*Model 2 (Robust)
regress lndifsumrbasef lnbaseavg p_white r_diverse p_bach_hig lnassesedvalue
homeowner, vce(robust)

*Model 3 (Robust)
regress lndifsumrbasef lnbaseavg p_white r_diverse p_bach_hig lnassesedvalue
homeowner built_b1960 built_a1983 n_stori_2 lnsqft nrms_3_5 nrms_8_mr
garage_sq_  twosfunits duplex halfplex nonsubdiv plannedunitd poolown
rooftype2 rooftype3, vce (robust)

*Model 4 (Robust)
regress lndifsumrbasef lnbaseavg p_white r_diverse p_bach_hig lnassesedvalue
homeowner built_b1960 built_a1983 n_stori_2 lnsqft nrms_3_5 nrms_8_mr
garage_sq_  twosfunits duplex halfplex nonsubdiv plannedunitd poolown
rooftype2 rooftype3 lnkenpop2010 lnkendwuden nesw ns nwse, vce (robust)

*Model 5 with Beta (Robust)
regress lndifsumrbasef lnbaseavg p_white r_diverse p_bach_hig lnassesedvalue
homeowner built_b1960 built_a1983 n_stori_2 lnsqft nrms_3_5 nrms_8_mr
garage_sq_ twosfunits duplex halfplex nonsubdiv plannedunitd poolown
rooftype2 rooftype3 lnkenpop2010 lnkendwuden nesw ns nwse greend100f
greden500 waterd100f waterd500f sth_e30ft sth_s30ft sth_w30ft sth_n30ft
sth_e60ft sth_s60ft sth_w60ft sth_n60ft, vce (robust)


*Model Diagnostics
twoway (scatter lndifsumrbasef lnbaseavg) (lfit lndifsumrbasef lnbaseavg)
twoway (scatter lndifsumrbasef lnassesedvalue) (lfit lndifsumrbasef
lnassesedvalue)
twoway (scatter lndifsumrbasef lnsqft) (lfit lndifsumrbasef lnsqft)
twoway (scatter lndifsumrbasef lnkenpop2010) (lfit lndifsumrbasef
lnkenpop2010)
twoway (scatter lndifsumrbasef greend100f) (lfit lndifsumrbasef greend100f)
twoway (scatter lndifsumrbasef sth_w60ft) (lfit lndifsumrbasef sth_w60ft)
histogram resid, norm

rvfplot
```

Chapter IV.

```
*Multiple Regression (robust with beta)
regress ln_RSM lnAvgHgt  ln_VarHgt ln_treeden, vce (robust) beta

*Checking Collinearity
vif
twoway (scatter ln_RSM ln_treeden) (lfit ln_RSM ln_treeden)
twoway (scatter ln_RSM lnAvgHgt) (lfit ln_RSM lnAvgHgt)
twoway (scatter ln_RSM  ln_VarHgt) (lfit ln_RSM  ln_VarHgt)

*Model Diagnostics
rvpplot  lnAvgHgt
rvpplot  ln_VarHgt
rvpplot  ln_treeden
predict resid, residuals
histogram resid, normal
rvfplot
```