

# Household Operational Energy Consumption in Urban China: A Multilevel Analysis on Jinan

By

Dong Wang

B.A. in Management (Urban & Regional Management)

B.A. in Economics

Peking University

Beijing, China (2010)

Submitted to the Department of Urban Studies and Planning  
in partial fulfillment of the requirements for the degree of

Master in City Planning

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2012

© 2012 Massachusetts Institute of Technology. All Rights Reserved

The author here by grants to MIT the permission to reproduce and to distribute publicly  
paper and electronic copies of the thesis document in whole or in part in any medium  
now known or hereafter created.

Author \_\_\_\_\_  
Department of Urban Studies and Planning  
August 30th, 2012

Certified by \_\_\_\_\_  
Professor P. Christopher Zegras  
Department of Urban Studies and Planning  
Thesis Supervisor

Accepted by \_\_\_\_\_  
Professor Alan Berger  
Chair, MCP Committee  
Department of Urban Studies and Planning



# **Household Operational Energy Consumption in Urban China: A Multilevel Analysis on Jinan**

By

Dong Wang

Submitted to the Department of Urban Studies and Planning  
in partial fulfillment of the requirements for the degree of  
Master in City Planning

## **ABSTRACT**

With decades of economic growth and socio-economic transformation, China's residential sector has seen rapid expansion in energy consumption, and is now the second largest energy consuming sector in the country. Faced with challenges of energy resource depletion and natural environment deterioration, China has been intensifying its efforts on energy conservation and emissions reductions in the residential sector.

In this thesis, I present an analysis of household operational energy consumption in urban China through empirical evidence from Jinan, the capital city of eastern China's Shandong Province. With data from a survey of approximately 4,000 households and spatial analysis of 23 urban neighborhoods, I summarize key household socio-economic and demographic characteristics, dwelling unit physical attributes, appliance ownership, and usage control, as well as neighborhood characteristics of density, mixed use, solar gain, and wind flow. Based on a multilevel regression model, I examine the household, neighborhood, and cross-level interaction effects on in-home operational energy consumption.

The research reveals that operational usage accounts for a predominantly large portion of total residential energy consumption in Jinan, and operational energy consumption patterns vary greatly across households in different neighborhood typologies. The multilevel analysis shows that six household characteristics are identified as having a positive, statistically significant relationship with greater energy usage: higher household income, presence of three or more adults and/or a child, larger dwelling unit area, and ownership of one or more air conditioners. Among neighborhood characteristics, higher floor area ratio is found to associate with lower operational energy consumption. In cross-level interaction effects, higher building function mix may weaken the positive effect of household income on operational energy consumption, and higher neighborhood porosity is correlated with higher energy consumption for households living on top floors and/or with electric heating.

Thesis Supervisor: P. Christopher Zengras

Title: Ford Career Development Associate Professor of Transportation and Urban Planning

Thesis Reader: Dennis M. Frenchman

Title: Leventhal Professor of Urban Design and Planning

## ACKNOWLEDGEMENT

The writing process of this thesis has been a most exciting and rewarding intellectual journey. I am tremendously grateful to many people who have been granting me support and encouragement throughout this year-long process.

I would like to extend my deepest gratitude to my thesis supervisor Prof. P. Christopher Zegras. I greatly appreciate that Chris led me into this research and offered me invaluable guidance and instruction. From the thesis topic selection at the beginning to the final revisions at the end, Chris has always been generously sharing with me his constructive comments with great patience. As an excellent teacher, mentor and scholar, Chris motivates me to explore further into quantitative research methods and inspires my academic curiosity of cities and energy.

My special thanks go to my thesis reader Prof. Dennis M. Frenchman. I have been hugely benefited from his insights and passion on applying academic research to transform urban landscape in the real world.

I wish to thank “Making the Clean Energy City” project for giving me such a wonderful opportunity to work on one of China’s most pressing issues. I am truly thankful to all of my colleagues in the project, especially Yang Chen, Rosie Sherman, Nah Yoon Shin, Cressica Brazier, Ruishan Zheng, and Feifei Yu, for their suggestions and support on my thesis research. I want to express my sincere thanks to the China Sustainable Energy Program of the Energy Foundation for sponsoring the project, and teams in Tsinghua University, Shandong University, and Beijing Normal University for initial data collection and processing. I acknowledge the Lloyd and Nadine Rodwin International Travel Fellowship for supporting my field work.

The two years at MIT has vastly enriched my life and expanded my scope curiosity. I am grateful to Prof. Karen R. Polenske, Prof. Tunney Lee, Prof. Yu-Hung Hong, Prof. Annette M. Kim, James Buckley and Patricia Molina Costa for all what I have learned in DUSP classrooms and studios. I feel also fortunate to have such amazing schoolmates, peers, and friends all around the campus who have brought me so many unforgettable memories.

And, to my dearest mom and dad, you are the best parents in the world, and I always cherish your care and love!

## Table of Contents

Abstract .....	3
Acknowledgement .....	4
Chapter 1: Introduction .....	13
1.1 Background: Energy Conservation and Emissions Reductions in China’s Residential Sector.....	15
1.2 Literature Review: Influencing Factors of Residential Energy Consumption .....	16
1.2.1 Household Effects .....	17
1.2.2 Neighborhood Effects .....	18
1.3 Focus: Household Operational Energy Consumption in Jinan.....	19
1.4 Research Question and Thesis Structure .....	20
Chapter 2: Context: Urban Neighborhoods in Jinan .....	22
2.1 Overview of Jinan .....	22
2.1.1 Shandong: China’s Key Agricultural and Industrial Producer .....	22
2.1.2 “South of the Ji River”: Hub of Transportation .....	24
2.1.3 Provincial Capital and Regional Economic Center .....	24
2.1.4 Urban Development: Historic Core and Growing Outskirts .....	25
2.2 Why Jinan? .....	26
2.2.1 Moderate City Scale.....	26
2.2.2 Representative Climate Pattern .....	29
2.2.3 Diverse Neighborhood Typologies .....	30
2.2.4 Thriving Urban Development .....	30
2.3 Selected Urban Neighborhoods.....	31
2.3.1 Traditional Neighborhoods.....	32
2.3.2 Grid Neighborhoods .....	35

2.3.3 Enclave Neighborhoods.....	38
2.3.4 Superblock Neighborhoods .....	40
Chapter 3: Data and Methods .....	45
3.1 Data .....	45
3.2 Method .....	47
Chapter 4: Overview of Household Operational Energy Consumption.....	49
4.1 Calculation of Operational Energy Consumption .....	49
4.1.1 Usage Ratios of Major Energy Sources.....	50
4.1.2 Calculation of Electricity Consumption .....	54
4.1.3 Calculation of Gas Consumption .....	54
4.1.4 Calculation of Coal Consumption.....	55
4.1.5 Calculation of Centralized Heating.....	56
4.2 Operational Energy Consumption Patterns .....	57
4.2.1 Energy Consumption Amount.....	57
4.2.2 Energy Consumption Share.....	61
4.3 Operational vs. Common Area, Transportation, and Embodied Energy Consumption Patterns.....	63
4.3.1 Energy Consumption Amount.....	63
4.3.2 Energy Consumption Share.....	65
4.4 Self-Reported Utility Data vs. Actual Energy Consumption .....	67
Chapter 5: Household Characteristics and Operational Energy Consumption.....	70
5.1 Household Survey Data .....	70
5.2 Overview of Household Characteristics .....	72
5.2.1 Socio-Demographic Status .....	72
5.2.2 Dwelling Physical Attributes .....	77

5.2.3 Appliance Ownership .....	79
5.2.4 Usage Control.....	82
5.3 Household Characteristics and Operational Energy Consumption .....	84
Chapter 6: Neighborhood Characteristics and Operational Energy Consumption .....	89
6.1 Neighborhood Geographic Information System Data .....	89
6.2 Overview of Neighborhood Characteristics .....	91
6.2.1 Density .....	91
6.2.2 Mixed Use .....	92
6.2.3 Solar Gain .....	95
6.2.4 Wind Flow .....	97
6.3 Neighborhood Characteristics and Operational Energy Consumption .....	98
Chapter 7: Multilevel Analysis: Household, Neighborhood, and Interaction Effects on Energy Consumption .....	103
7.1 Analysis of Variance within and between Neighborhoods.....	103
7.1.1 First Level: Variance within Neighborhoods .....	104
7.1.2 Second Level: Variance between Neighborhoods .....	104
7.1.3 Results: Significant Variation at Both Levels .....	105
7.2 Multilevel Regression Model .....	107
7.2.1 Level-1 Model: Household Characteristics .....	108
7.2.2 Level-2 Model: Neighborhood Characteristics .....	110
7.2.3 Results: Significant Household, Neighborhood, and Interaction Effects .....	111
7.3 Analysis of Multilevel Regression Results .....	113
7.3.1 Effects of Household Characteristics.....	114
7.3.2 Effects of Neighborhood Characteristics.....	116
7.3.3 Cross-Level Interaction Effects.....	117

7.3.4 Visualization of Interaction Effects .....	119
Chapter 8: Conclusion and Discussion.....	122
8.1 Conclusions.....	122
8.1.1 Patterns of Household Operational Energy Consumption.....	122
8.1.2 Variations of Household and Neighborhood Characteristics .....	124
8.1.3 Evidence of Household, Neighborhood, and Interaction Effects on Operational Energy Consumption.....	125
8.2 Policy Implications.....	127
8.2.1 More Energy-Saving Emphasis Placed on Household Operational Energy Consumption.....	127
8.2.2 Address Operational Energy Consumption in Diverse Urban Settings.....	128
8.2.3 Promote Energy Efficiency while Improving Living Conditions and Comfort.....	129
8.2.4 Encourage Energy-Efficiency Neighborhood Design .....	129
8.3 Research Limitations and Future Directions .....	130
8.3.1 Inconsistency of Survey.....	131
8.3.2 Inaccuracy of Energy Consumption Data.....	131
8.3.3 Lack of Additional Household and Neighborhood Characteristics Data .....	132
8.3.4 Methodological Constraints .....	132
8.3.5 Directions for Other Improvements .....	134
Bibliography.....	135



## List of Figures

Figure 1 - 1 Per Capita Energy Production and Consumption of China, 1980-2009.....	13
Figure 1 - 2 Growth Rates of Gross Domestic Product and Energy Consumption of China, 1980-2009 .....	14
Figure 1 - 3 Composition of Total Energy Consumption of China, 1995-2009.....	16
Figure 2 - 1 Location of Shandong Province .....	23
Figure 2 - 2 Urban Expansion of Jinan, Ancient-2003.....	25
Figure 2 - 3 Administrative and Urban Areas of Selected Sub-Provincial Cities and Provincial Capitals in China.....	28
Figure 2 - 4 Administrative-Area and Urban Populations of Selected Sub-Provincial Cities and Provincial Capitals in China .....	28
Figure 2 - 5 Precipitation and Temperature of Jinan, 1971-2000.....	29
Figure 2 - 6 Jinan West (High-Speed) Railway Station .....	31
Figure 2 - 7 Locations of 23 Selected Urban Neighborhoods in Jinan .....	32
Figure 2 - 8 Traditional Neighborhood: Furong .....	33
Figure 2 - 9 Traditional Neighborhood Map: Zhang Village .....	34
Figure 2 - 10 Grid Road System in Jinan.....	36
Figure 2 - 11 Grid Neighborhood: Commercial .....	37
Figure 2 - 12 Grid Neighborhood Map: Commercial North.....	38
Figure 2 - 13 Enclave Neighborhood: Dongcang .....	39
Figure 2 - 14 Enclave Neighborhood Map: Foshanyuan .....	40
Figure 2 - 15 Superblock Neighborhood: Mingshi.....	42
Figure 2 - 16 Superblock Neighborhood Map: Sunshine 100 .....	43
Figure 3 - 1 Data Framework.....	46

Figure 3 - 2 Methodological Framework .....	48
Figure 4 - 1 Natural Gas Usage Ratios of Surveyed Neighborhoods.....	51
Figure 4 - 2 Coal Usage Ratios of Surveyed Neighborhoods.....	52
Figure 4 - 3 Centralized Heating Usage Ratios of Surveyed Neighborhoods .....	53
Figure 4 - 4 Annual Per Household Operational Energy Consumption Amounts By Energy Source of Surveyed Neighborhoods .....	58
Figure 4 - 5 Annual Per Household, Per Capita, and Per Square Meter Operational Energy Consumption in Surveyed Neighborhoods .....	60
Figure 4 - 6 Annual Operational Energy Consumption Shares By Energy Source of Surveyed Neighborhoods.....	62
Figure 4 - 7 Annual Per Household Operational, Common Area, Transportation, and Embodied Energy Consumption Amounts of Surveyed Neighborhoods.....	64
Figure 4 - 8 Annual Total Energy Consumption Shares of Surveyed Neighborhoods .....	66
Figure 4 - 9 Self-Reported and Actual Annual Electricity Consumption of Selected Neighborhoods.....	68
Figure 4 - 10 Distribution Patterns of Differences between Self-Reported and Actual Electricity Consumption Data .....	69
Figure 5 - 1 Number of Households Surveyed in Surveyed Neighborhoods .....	71
Figure 5 - 2 Annual Household Incomes of Surveyed Neighborhoods .....	73
Figure 5 - 3 Average Household Sizes of Surveyed Neighborhoods.....	74
Figure 5 - 4 Percentages of Rental Units in Surveyed Neighborhoods.....	76
Figure 5 - 5 Average Dwelling Unit Areas of Surveyed Neighborhoods .....	78
Figure 5 - 6 Household Air Conditioner Ownership of Surveyed Neighborhoods .....	80
Figure 5 - 7 Household Solar Water Heater Ownership of Surveyed Neighborhoods .....	81
Figure 5 - 8 Percentages of Households with Electric Heating in Surveyed Neighborhoods .....	83

Figure 5 - 9 Relationship between Annual Household Income and Operational Energy Consumption .....	85
Figure 5 - 10 Relationship between Household Size and Operational Energy Consumption .....	86
Figure 5 - 11 Relationship between Dwelling Unit Area and Operational Energy Consumption	87
Figure 5 - 12 Relationship between Air Conditioner Ownership and Operational Energy Consumption .....	88
Figure 6 - 1 Floor Area Ratios of Surveyed Neighborhoods .....	92
Figure 6 - 2 Building Function Mix Indices of Surveyed Neighborhoods .....	94
Figure 6 - 3 Summer Solar Gain Indices of Surveyed Neighborhoods .....	96
Figure 6 - 4 Porosity Indices of Surveyed Neighborhoods .....	98
Figure 6 - 5 Relationship between Floor Area Ratio and Operational Energy Consumption .....	99
Figure 6 - 6 Relationship between Building Function Mix and Operational Energy Consumption .....	100
Figure 6 - 7 Relationship between Summer Solar Gain Index and Operational Energy Consumption .....	101
Figure 6 - 8 Relationship between Porosity and Operational Energy Consumption .....	102
Figure 7 - 1 Visualization of Interaction Effects .....	120
Figure 8 - 1 Comparison of Annual Household Operational Energy Consumption between Jinan and the United States .....	124

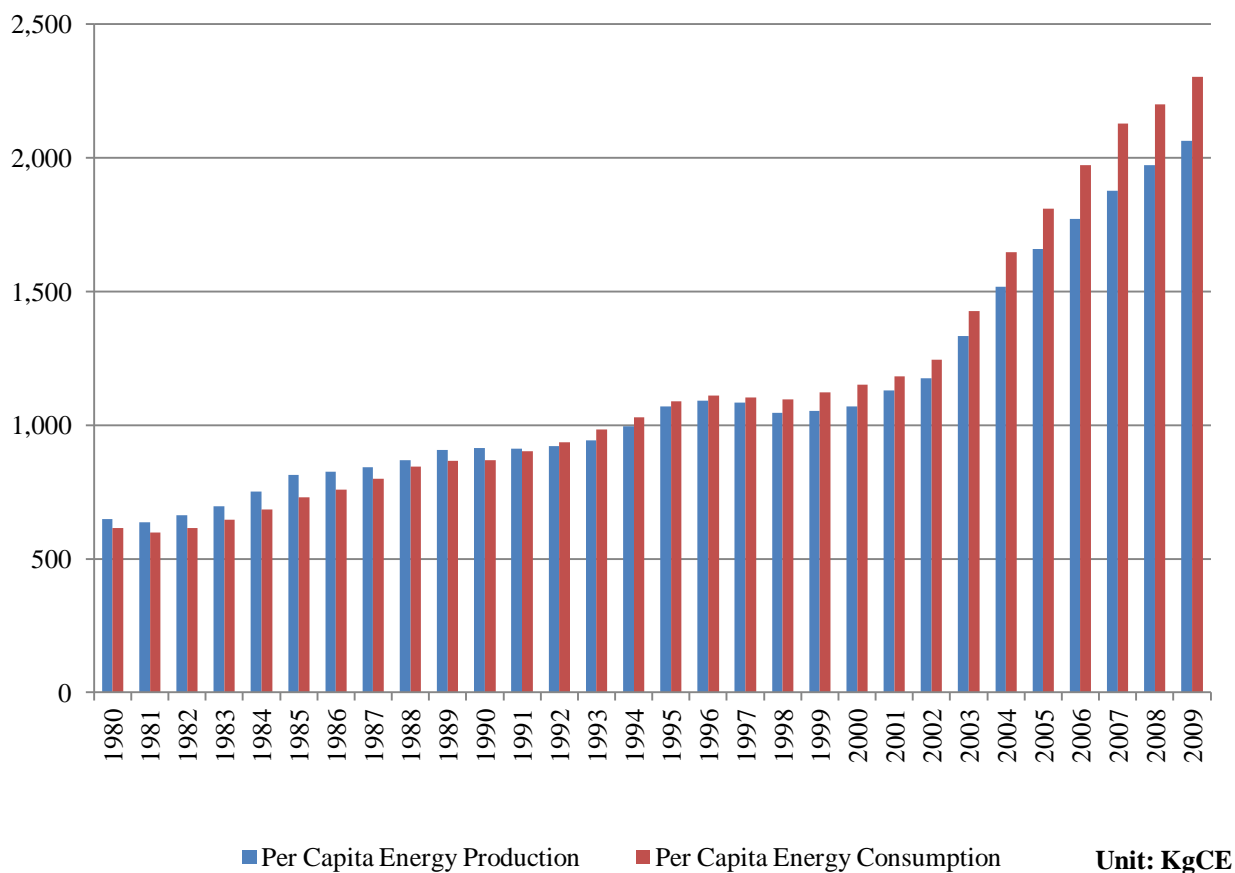
## **List of Tables**

Table 2 - 1 Key Statistics Information of Jinan, 2009.....	22
Table 2 - 2 Administrative Divisions of Jinan.....	27
Table 4 - 1 Major Operational Energy Sources of Surveyed Neighborhoods .....	50
Table 6 - 1 Selected Neighborhood Characteristics of Four Typologies .....	90
Table 7 - 1 Analysis of Variance Results of Household Operational Energy Consumption within and between Neighborhoods in Jinan.....	106
Table 7 - 2 Maximum Likelihood Estimation of Multilevel Regression Model Results .....	112
Table 7 - 3 Household, Neighborhood and Interaction Effects on Operational Energy Consumption in Jinan .....	113

## Chapter 1: Introduction

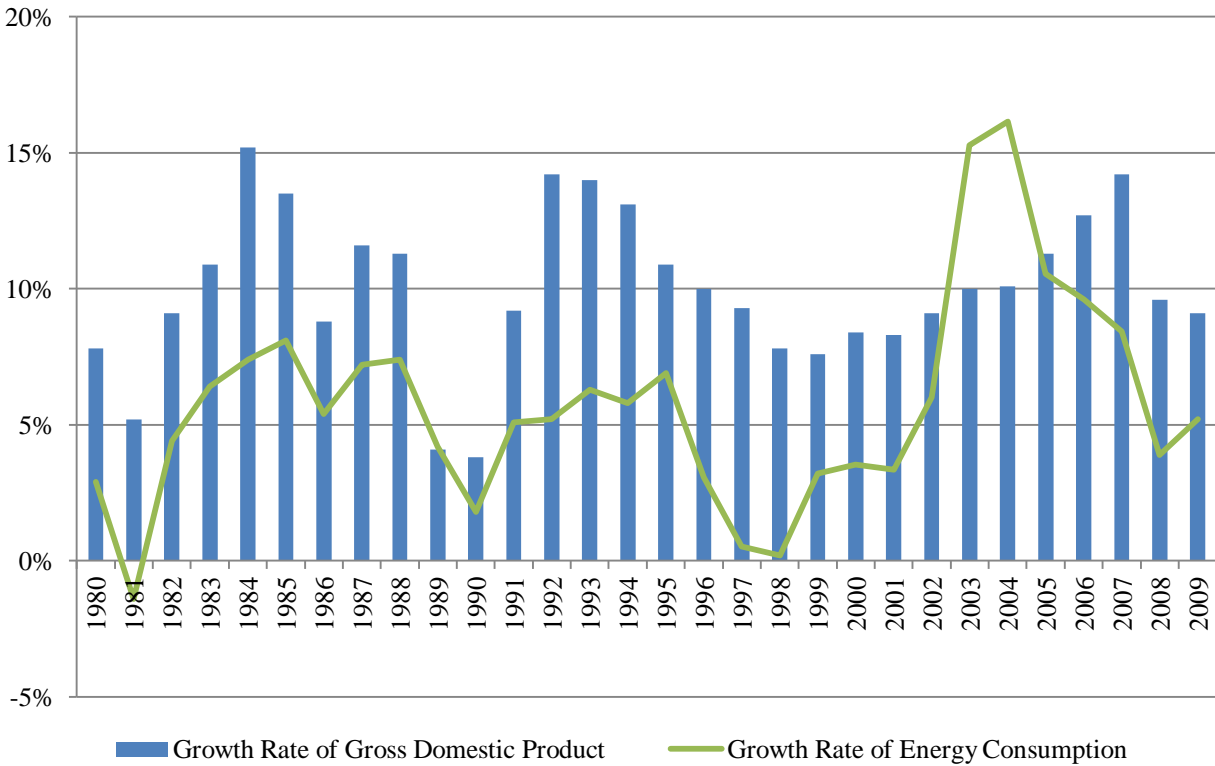
With rapid economic growth, China has seen its energy consumption dramatically growing over the recent three decades (see Figures 1 - 1 and 1 - 2). China has overtaken the United States to become the largest energy consumer in the world (International Energy Agency, 2010), and its energy consumption has surpassed energy production since the early 1990s.

**Figure 1 - 1 Per Capita Energy Production and Consumption of China, 1980-2009**



*Source: National Bureau of Statistics of China, 2010*

**Figure 1 - 2 Growth Rates of Gross Domestic Product and Energy Consumption of China, 1980-2009**



*Source: National Bureau of Statistics of China, 2010*

The boom of industrial and commercial activities has increased China’s demand for energy. At the same time, the rising living standards of Chinese households have also greatly contributed to the expansion of energy consumption in the residential sector.

Chinese households are increasingly embracing lifestyles that encourage higher levels of energy consumption—living in larger housing units, owning more home appliances, and traveling more often by driving. Chinese residential neighborhoods are also increasingly adopting design and management attributes that promote energy consumption, such as more high-rises equipped with elevators and high-powered water pumps, and larger underground parking spaces. Transformations in both China’s household and neighborhood characteristics have led to fast growing energy consumption in the residential sector.

In this thesis, I examine China's residential energy consumption through the lens of Jinan's household operational energy consumption. Based on the results from a large-scale survey of approximately 4,000 households in 23 urban neighborhoods, I present a thorough analysis of operational energy consumption patterns among the surveyed Jinan households, and investigate the influences of household and neighborhood characteristics on household operational energy consumption.

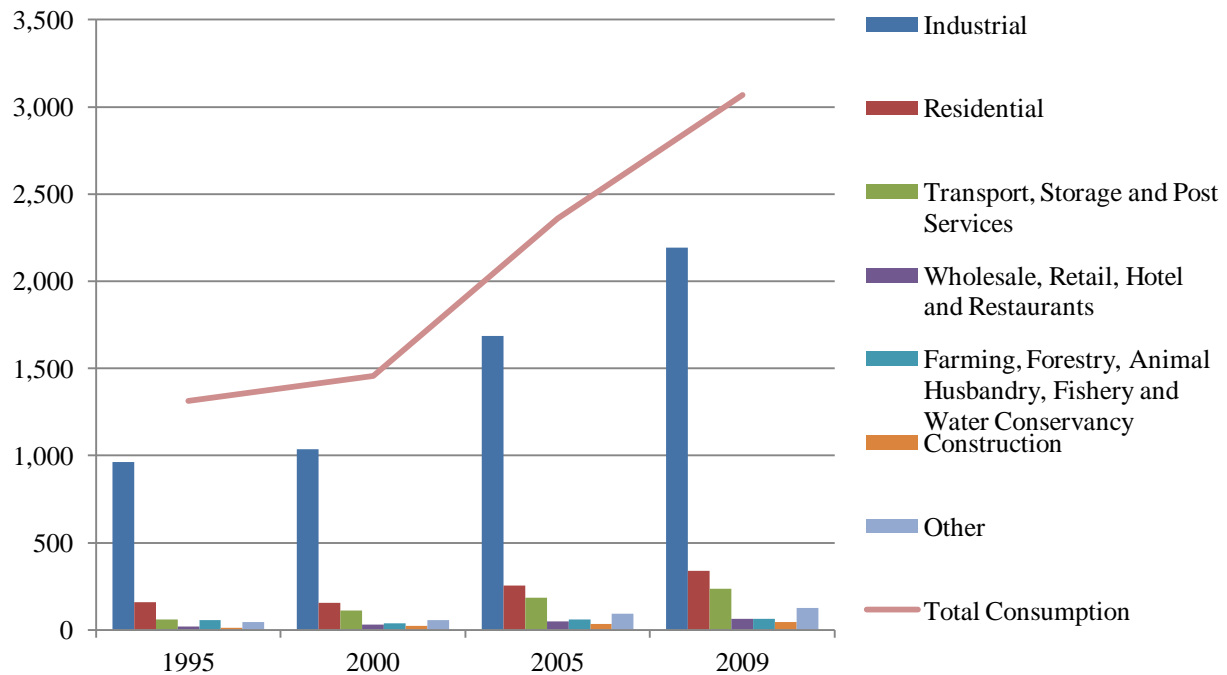
## **1.1 Background: Energy Conservation and Emissions Reductions in China's Residential Sector**

With an ambition to upgrade its economic structure and to respond to energy resource depletion and natural environment deterioration, China's central government has started to initiate strict restrictions and ambitious requirements on provincial and local governments in order to achieve energy conservation and emissions reductions. China has reduced its national average energy consumption per unit of GDP by 19.1% from 2006 to 2010 in its eleventh five-year plan (National Development and Reform Commission, 2011), and has further mandated a 16% decrease of energy consumption per unit of GDP by 2015 compared to the 2010 level in its twelfth five-year plan (General Office of the State Council, 2011).

The residential sector is the second largest energy consumption category in China; however, compared with the large share of industrial energy use, the residential sector only accounts for roughly 10% of China's total annual energy consumption (see Figure 1 - 3). As a result, most current regulations and practices promoting energy efficiency in China still emphasize the adjustment and upgrade of the industrial sector.

However, the fast growing speed of residential energy consumption has pushed the Chinese government to realize the importance of energy conservation and emissions reductions in the residential sector. In the twelfth five-year plan, China has explicitly required household energy consumption reductions and building energy conservation through planning, legislation, technology, standards, and design (General Office of the State Council, 2011).

**Figure 1 - 3 Composition of Total Energy Consumption of China, 1995-2009**



Unit: million KgCE

Source: National Bureau of Statistics of China, 2010

## 1.2 Literature Review: Influencing Factors of Residential Energy Consumption

Noting that Chinese cities are experiencing major growth and pattern changes in energy consumption in the residential sector, the literature argues that it is important to identify challenges and provide policy advice to promote residential energy efficiency (Ouyang and Ge, 2009; Zhou et al., 2009; Zhang, 2010; Jiang, 2010; Zhao et al., 2011).

In the realm of empirical analysis of energy consumption in China's urban residential sector, scholars have mainly approached this topic focusing on two aspects: household effects and neighborhood effects on residential energy consumption.



### 1.2.1 Household Effects

Household effects are one of the most important factors influencing energy consumption in the residential sector. Research findings across the globe suggests that, despite variations in climate patterns and energy sources, household characteristics such as socio-economic status, appliance ownership, and occupant behavior heavily impact residential energy consumption (Wilhite et al., 1996; Tuan et al., 1996; O'Neill and Chen, 2002; Ach ̃o and Schaeffer, 2009; Wiedenhofer et al., 2012).

Schuler (2000) and Pachauri (2004) suggest that household income and household size are the two most significant variables determining household energy consumption. Such a claim is reflected in the Chinese context as the change of socio-economic status of Chinese households is widely identified as a key driver of residential energy consumption. Pachauri and Jiang (2008) identify income level, together with urbanization, energy access, and energy prices, as one of the most important factors of the household energy transition in China. Xie et al. (2007) find higher household income leads to greater residential energy consumption based on a survey in Changsha, China. Zha et al. (2010) argue that rising income, a growing economy and improving living standards have led Chinese households to obtain “a quality life” of comfortable living and convenient traveling by consuming more energy. Zhou et al. (2003) and Liu et al. (2005) point out that demographic trends in China, including massive migration from rural to urban areas and increasing popularity of nuclear families, have also led to higher residential energy consumption.

The growth of appliance ownership is closely associated with Chinese households' rising socio-economic status, and has also boosted energy consumption. Zhang (2010) concludes that ownership of home appliances, including air conditioner, fridge, desktop computer, and solar water heater, may have positive correlations with household operational energy consumption. Zhou et al. (2009) suggest that the dramatic increase in air conditioner ownership will be the key driving force of China's residential energy consumption in the 2010s. In addition, China's growing vehicle ownership has also resulted in greater energy consumption for households' traveling purposes (Riley, 2002; Deng, 2007; Ni, 2008). Even though such increases may be reflected in the transportation rather than the residential sector, it is directly caused by and highly connected with effects from the households' lifestyle.

Occupant behavior also has a strong influence on residential energy consumption. Studies have shown that operational energy consumption is influenced by occupants' daytime presence (Santin, 2009) and indoor temperature preference for heating and cooling (Linden, 2006). In the Chinese context, based on a household survey in Hangzhou, Ouyang and Hokao (2009) discover that improving occupants' behavior in domestic life, such as setting higher air conditioner temperature, reducing refrigerator door open times, eliminating needless lighting, and unplugging electrical appliances when not in use, can save more than 10% of household electricity use.

### **1.2.2 Neighborhood Effects**

The literature concludes that the physical attributes of residential buildings and neighborhoods have significant impacts on residential energy consumption. Santin (2009) summarizes a group of building physical features that may impact residential energy consumption, including vintage of building, type of dwelling, design of dwelling, insulation, and heating system. Worldwide, research has shown that optimized design and retrofit of residential buildings can result in improved energy performance (Verbeeck and Hens, 2005; Tommerup and Svendsen, 2006; Lollini et al., 2006). In the Chinese context, Zhao and Lin (2005), Zhao (2007), and Ouyang et al. (2009) explore energy-efficient design and renovations of existing residential buildings, and identify potential economic savings and environmental benefits by adopting energy-saving measures.

At the neighborhood level, the air and thermal performance of neighborhood physical attributes and construction materials have a large influence on energy consumption. Jiang (2010) and Zhang (2010) provide evidence that the typology and form of Chinese neighborhoods make an apparent difference in their total energy consumption. The gated, high-rise superblock neighborhoods not only yield higher operational and common area energy consumption, but also apparently encourage the ownership and usage of automobiles, which both contribute to the result that the superblocks are the highest energy consuming neighborhood typology.

Besides the traditional focuses on buildings and neighborhoods in a physical context, neighborhood energy management also helps to shape urban form and infrastructure patterns to a more environmentally sustainable path by taking urban land use and infrastructure planning into

consideration. The specific strategies mentioned in the literature include replacing decentralized coal combustion for individual dwellings with community facilities, developing co-generation and large-scale, integrated district-level energy systems, and encouraging mixed land use and density. Sadownik and Jaccard (2001) suggest that China can achieve urban residential and transportation emissions reductions of approximately 14% for carbon dioxide (CO<sub>2</sub>), 10% for sulfur dioxide (SO<sub>2</sub>), 40% for nitrogen oxides (NO<sub>x</sub>), and 14% for particulate emissions in 2015 by adopting certain measures of energy management.

### **1.3 Focus: Household Operational Energy Consumption in Jinan**

China has intensified its efforts on energy conservation and emissions reductions in the residential sector, and the literature has reached a consensus that both household and neighborhood effects exert influences on residential energy consumption. In this thesis, I select Jinan as a case study, and place my focus on the analysis of household operational energy consumption in urban China.

Jinan is the capital city of Eastern China's Shandong Province, and one of China's 15 sub-provincial level cities. The primary data employed by this thesis come from "Making the Clean Energy City in China", a multi-year research project sponsored by the Energy Foundation's China Sustainable Energy Program and a collaboration involving the Massachusetts Institute of Technology, Tsinghua University, Beijing Normal University, and Shandong University. The project has conducted surveys of approximately 4,000 households and gathered the geographic information systems (GIS) data for 23 residential neighborhoods in Jinan. These data provide the empirical foundation for the quantitative analysis of this research.

In this thesis, household operational energy consumption is defined as the energy consumed by households to maintain the indoor operational functions of their daily life. It includes the four typical energy sources for operational energy consumption of Jinan households—electricity, natural gas, coal, and centralized heating. Operational energy consumption captures the energy used by indoor home devices for purposes such as lighting, cooking, space and water heating, and entertainment. Beyond operational energy consumption, household energy use in residential neighborhoods also includes common area, transportation, and embodied energy consumption. Common area energy consumption consists of energy use in public spaces for water pumps,

lighting, elevators, access security, and underground parking. Transportation energy consumption consists of energy consumed by travel (for work, maintenance, leisure, etc.). The embodied energy consumption accounts for the energy consumed in the construction process of the neighborhoods.

#### **1.4 Research Question and Thesis Structure**

Based on the household survey and neighborhood GIS data, I aim to answer the question: what is the relationship between operational energy consumption and household and neighborhood characteristics in Jinan? I will calculate estimates of household operational energy consumption in Jinan, interpret energy consumption behavior and patterns, and analyze the relevant relationships using quantitative methods.

The thesis is composed of eight chapters. After this initial introduction, Chapter 2 details the research context by summarizing the geographical, economic, historical, and urban development information of Jinan, and describing the key characteristics of the 23 neighborhoods categorized by four distinctive urban neighborhood typologies covered in this study.

Chapter 3 presents the framework of the quantitative analysis that aims to capture both household and neighborhood effects on operational energy consumption and describes the data collection and processing utilized in this study.

Chapter 4 introduces the calculations of estimated household operational energy consumption and the shares of electricity, natural gas, coal, and centralized heating—the four major energy sources included in the study. In the chapter, I will also make comparisons of operational energy consumption with common area, transportation, and embodied energy consumption of the neighborhoods, and briefly discuss the validity of the calculation methods.

Chapters 5 and 6 present the key household and neighborhood characteristics of the valid observations covered in this study. Chapter 5 illustrates the characteristics of socio-economic and demographic status, physical attributes of the dwelling, appliance ownership, and usage control of 3,831 sampled households; Chapter 6 displays the characteristics of density, mixed use, solar gain, and wind flow of the 23 neighborhoods. The two chapters also briefly explore the

relationships between household and neighborhood characteristics and operational energy consumption.

Chapter 7 applies multilevel regression modeling techniques to investigate the statistical correlations of operational energy consumption and selected household and neighborhood effects. In the chapter, I conclude that significant variation in operational energy consumption exists within and between residential neighborhoods in Jinan, and explain the household, neighborhood, and cross-level effects that exert apparent influences on operational energy consumption.

Chapter 8 concludes the thesis, summarizing the key research findings and policy implications, as well as limitations and potential directions for future studies.

## Chapter 2: Context: Urban Neighborhoods in Jinan

I will introduce the context of the selected urban neighborhoods in Jinan in this chapter. First, I will present a summary of Jinan and Shandong's key geographical, economic, historical, and urban development information. I will then discuss in detail why Jinan makes a representative and convincing case for this study from the perspectives of city scale, climate pattern, neighborhood typologies, and urban development opportunities. I conclude this chapter by introducing the 23 urban neighborhoods that have been covered in the survey, categorizing them into four distinctive typologies (traditional, grid, enclave, and superblock) and illustrating their characteristics.

### 2.1 Overview of Jinan

As a provincial capital and one of China's 15 sub-provincial cities, Jinan is a well-known regional economic and transportation center and a popular tourist destination in eastern China. Jinan's key statistics are summarized in Table 2-1.

**Table 2 - 1 Key Statistics Information of Jinan, 2009**

<b>Area</b>	<b>Sub-Provincial</b>	8,001 km <sup>2</sup> (3,089.1 sq mi)
	<b>Urban</b>	3,257 km <sup>2</sup> (1,257.5 sq mi)
<b>Population</b>	<b>Sub-Provincial</b>	6.81 million
	<b>Urban</b>	3.25 million
<b>Gross Domestic Product</b>	<b>Total</b>	335.1 billion CNY (52.5 billion USD)
	<b>Per Capita</b>	49,391 CNY (7,750 USD)

*Source: National Bureau of Statistics of China, 2009*

#### 2.1.1 Shandong: China's Key Agricultural and Industrial Producer

Jinan is the capital and the largest city of Shandong Province in eastern China. Literally meaning "East of the Mountains" in Chinese, Shandong is located on the eastern edges of

northern China's Taihang Mountains. Situated on the North China Plain and along the Yellow River, Shandong extends its territory onto the Shandong Peninsula, which borders the Bohai Sea to the north and the Yellow Sea to the south (see Figure 2 - 1). Shandong is located in the middle point of China's northern coastline between Beijing and Shanghai, and the eastern tip of its Peninsula is adjacent to the Republic of Korea and Japan. Such geographic convenience has given rise to the prosperity of trade and commerce in the province.

**Figure 2 - 1 Location of Shandong Province**



*Source: ChinaToday.com, 2006*

Shandong is the country's second most populous province after Guangdong, with 95.80 million people and accounting for 7.2% of China's total population (National Bureau of Statistics of China, 2011). With a large population base and as a key agricultural and industrial producer in the country, Shandong has long been one of China's most economically developed provinces. Shandong's gross domestic product (GDP) ranks third among all provinces, municipalities, and autonomous regions in China, after Guangdong and Jiangsu, contributing slightly less than 10% of the total national GDP (National Bureau of Statistics of China, 2011).

### **2.1.2 “South of the Ji River”: Hub of Transportation**

Jinan’s name originates from the Ji River, which used to flow to the north of the city. Jinan, literally meaning “South of the Ji River”, and its nickname “City of Springs” (Quancheng) both refer to its unique landscape that used to be abundant in water. However, after the Ji River dried up in 1852 when the Yellow River changed its course (Pletcher, 2011), and due to the overuse and pollution of underground water, Jinan has faced severe water shortages, especially in recent years (Xinhua, 2012).

Located in mid-west Shandong, Jinan enjoys a favorable geographical environment and transportation connections. Jinan sits at the intersection of China National Highways 104, 220, and 309. Jinan is also at the crossroad of China’s two main railways—the Beijing-Shanghai Railway, one of China’s three major north-south rail corridors; and Jiaoji Railway, which connects Jinan and Qingdao, Shandong’s two major cities. Jinan is situated on the Beijing-Shanghai High-Speed Railway, and the east-west running Qingdao-Taiyuan High-Speed Railway, which is under construction and connects Jinan to central-north China (Xinhua, 2010).

### **2.1.3 Provincial Capital and Regional Economic Center**

Jinan has been the capital of Shandong since 1376, and has always been the political, economic, and cultural center of the province (Jinan Government, 2007). The economic affluence of Shandong and the geographical distinction of Jinan have made the city one of China’s most important provincial capitals.

Jinan was designated as a sub-provincial city in 1994. Sub-provincial cities in China are special administrative units that have higher administrative rankings than regular city-level jurisdictions. These are usually the cities with the highest economic production, and are entitled to enjoy certain levels of freedom in economic and social development. The legal status of sub-provincial cities is below that of municipalities, which are equivalent to provinces, but above regular prefecture-level cities, which are directly under the rule of provincial-level governments. Jinan and Qingdao are the only two sub-provincial cities in Shandong Province.

Jinan is also a major regional economic center in Shandong. Historically, Jinan served as the main hub for trading agricultural goods and manufacturing light industry products, with a thriving textile and clothing industry (Jinan Government, 2007). However, business and

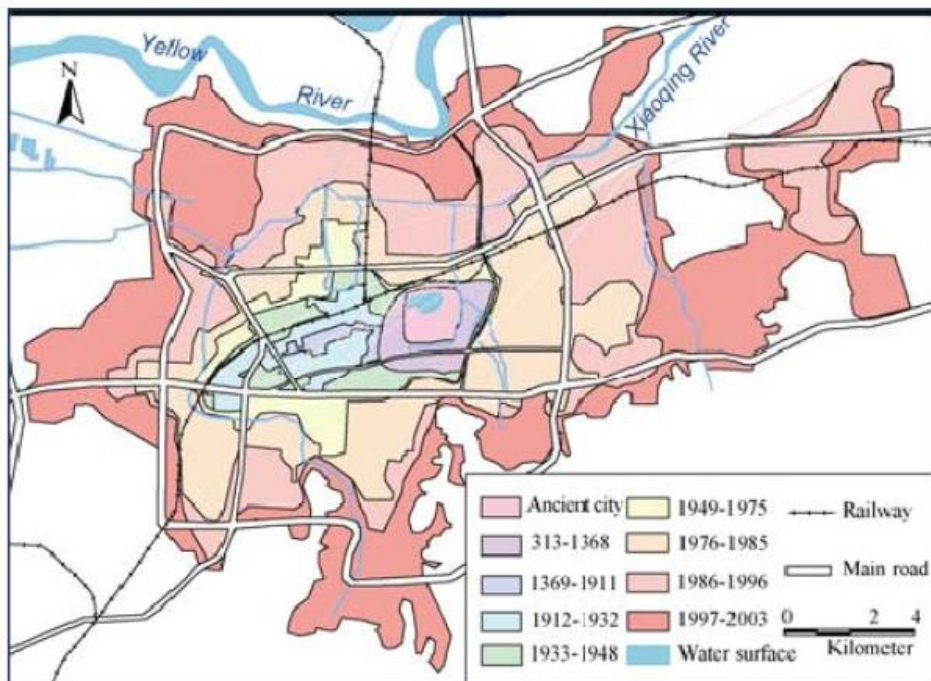


commercial activities were heavily struck during the Chinese Civil War in the 1940s. From the 1950s, Jinan was transformed into a heavy industrial city with the introduction of large-scale state-owned chemical, construction vehicle, and iron and steel plants (Jinan Government, 2007). Since the 1990s, the city has been pursuing economic growth in the service sectors, including real estate, tourism, logistics industry, and information technology (Jinan Government, 2012).

#### 2.1.4 Urban Development: Historic Core and Growing Outskirts

With a continued civilization of over 2,700 years (Jinan Government, 2007), Jinan has an urban landscape that has been shaped and structured by multiple rounds of planning and construction and influenced by both Chinese and western cultures. Traditional Chinese-style courtyards and alleys are commonly seen in Jinan’s historical city center, though rapid urban redevelopment in recent years has seen many of them demolished and replaced by modern-style high-rises and skyscrapers. Jinan’s old Commercial Port (“Shangbu”) is characterized by a western-style grid street system, indicating its colonial history as a German concession before World War I.

**Figure 2 - 2 Urban Expansion of Jinan, Ancient-2003**



*Source: Yu et al., 2006*

Jinan’s outskirts have been rapidly developing since the 1980s. As China granted compensated transaction of land use rights to private entities, new residential, commercial, industrial and transportation constructions have rapidly expanded the city boundary (see Figure 2 - 2).

## **2.2 Why Jinan?**

Jinan is selected in this study as a case to investigate household operational energy consumption in urban China. This study is a part of the “Making the Clean Energy City in China” Project, a collaborative initiative involving Massachusetts Institute of Technology and multiple Chinese university partners supported by the China Sustainable Energy Program of the Energy Foundation.

The availability of data and financial and staff support are crucial prerequisites of selecting Jinan as the key context of this research. However, other factors—including city scale, climate pattern, neighborhood typologies, and urban development opportunities—are also compelling reasons for why Jinan is a good case to investigate in order to understand household operational energy consumption in a typical Chinese urban setting.

### **2.2.1 Moderate City Scale**

Jinan’s area, population, and gross domestic product are all around the average of first-tier Chinese cities. This moderate city scale makes Jinan a reasonably representative case for comparison with other Chinese cities.

Similar to most other Chinese cities, the “City of Jinan” has two layers of jurisdictions—a larger administrative area and a core urban area. The administrative unit carries a broader boundary composed of an urban core and surrounding rural areas, and the urban area only includes the city core of high density. Therefore, on the one hand, the “City of Jinan” refers to the whole sub-provincial division, which consists of six districts, three counties, and a county-level city (see Table 2-2). On the other hand, the “City” also often denotes just the urban area of Jinan, which only includes four whole districts (Lixia, Shizhong, Huaiyin, and Tianqiao) and part of the other two districts (Licheng and Changqing). The urban area does not include any of the three counties or the city-level city (Zhangqiu).

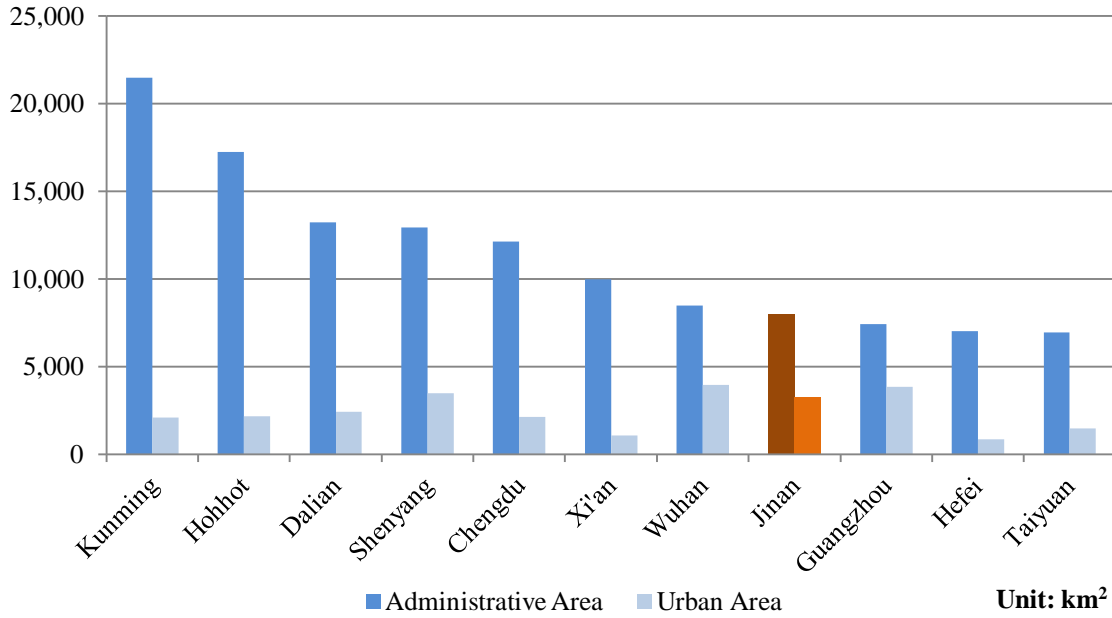
**Table 2 - 2 Administrative Divisions of Jinan**

<b>Administrative Division</b>	<b>Area (km<sup>2</sup>)</b>
Lixia District	100.87
Shizhong District	280.33
Huaiyin District	151.65
Tianqiao District	258.71
Licheng District	1,303.88
Changqing District	1,208.54
Pingyin County	715.18
Jiyang County	1,097.15
Shanghe County	1,163.19
Zhangqiu City	1,721.29
<b>Jinan</b>	<b>8,000.79</b>

*Data Source: National Bureau of Statistics of China, 2010*

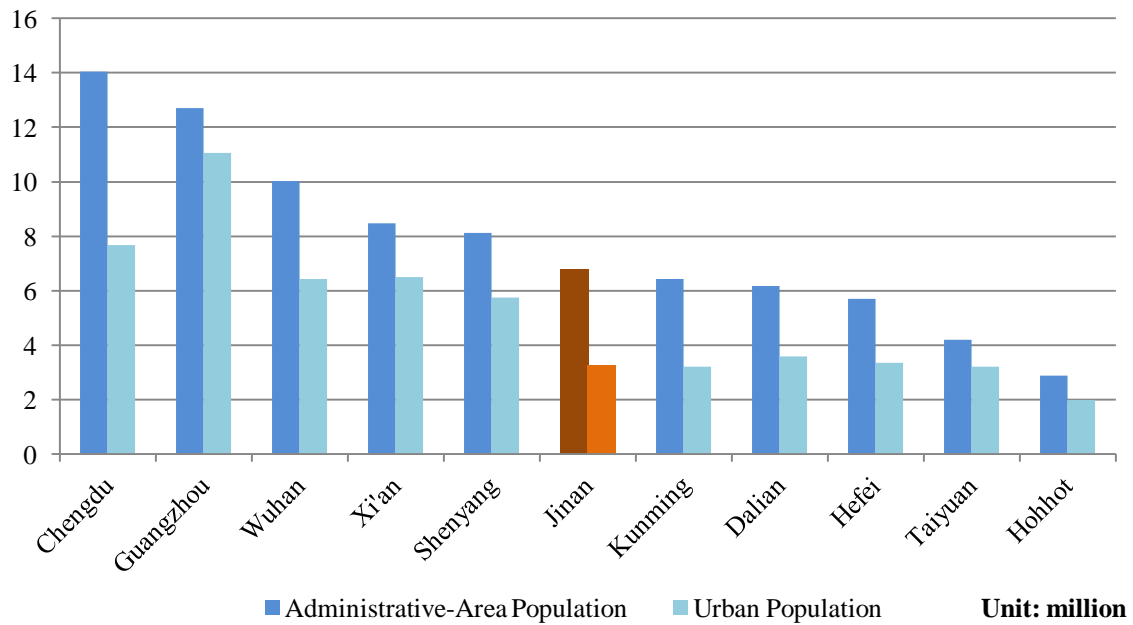
Both the areas and populations of Jinan's administrative and urban jurisdictions are on the average of typical sub-provincial cities and provincial capitals in China (see Figures 2 - 3 and 2 - 4). Such moderate geographic scale facilitated the implementation of the household surveys and strengthens the generalization from the research findings.

**Figure 2 - 3 Administrative and Urban Areas of Selected Sub-Provincial Cities and Provincial Capitals in China**



Data Source: National Bureau of Statistics of China, 2011

**Figure 2 - 4 Administrative-Area and Urban Populations of Selected Sub-Provincial Cities and Provincial Capitals in China**

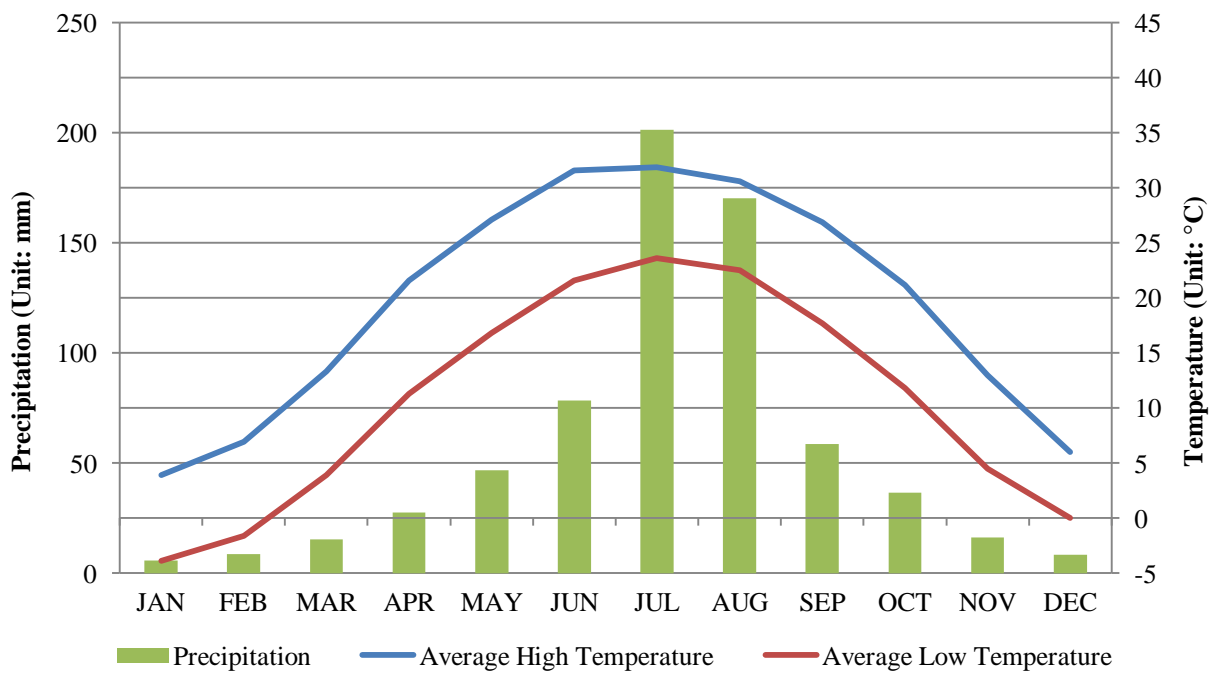


Data Source: National Bureau of Statistics of China, 2011

### 2.2.2 Representative Climate Pattern

Jinan lies between continental and subtropical climate zones, the two dominant climate zones along China's coastal area. Jinan has four well-defined seasons with a hot and rainy summer, and a dry and cold winter (National Meteorological Center of China Meteorological Administration, 2012). Compared to other cities in northern China, Jinan's precipitation is slightly higher; however, as Jinan's city center is surrounded by mountains, the summer is humid and hot. In general, Jinan's climate pattern is representative and comparable to many other cities in northern and eastern China.

**Figure 2 - 5 Precipitation and Temperature of Jinan, 1971-2000**



*Data Source: China Meteorological Data Sharing Service System, 2012.*

Such a representative climate pattern is important when studying household operational energy consumption. The climate pattern can heavily influence household appliance ownership and usage, which may further exert powerful impacts on occupants' energy consumption behavior. In the case of Jinan, air-conditioners are widely used in the summer as July's average high temperature reaches 31.9 °C (89 °F). Centralized heating systems are also commonly seen in most urban neighborhoods as the average low temperature in January is -3.9 °C (25 °F) (see

Figure 2 - 5). Jinan's climate helps to reveal the typical energy consumption pattern of China's urban households because air-conditioners and centralized heating usually account for crucial shares of operational energy consumption in China.

### **2.2.3 Diverse Neighborhood Typologies**

As I will further introduce in the following section, Jinan's urban neighborhoods can be mainly classified into four typologies—traditional, grid, enclave, and superblock. These four typologies represent urban development phases from the pre-1910s to the contemporary era, and collectively cover most forms of urban neighborhoods in the city. Ranging from traditional Chinese-style courtyard houses to modern gated neighborhoods of high-rises and underground parking, Jinan's neighborhood typologies are typical and comparable with most other Chinese cities.

This study is intended to reveal, in part, the linkages between urban form characteristics and household energy consumption in China. The diverse yet representative urban neighborhood typologies in Jinan present a good opportunity to compare and analyze such connections.

### **2.2.4 Thriving Urban Development**

Jinan is faced with abundant urban development opportunities, due to expected urban population growth and improved transportation connectivity, including the newly completed high-speed railway.

Shandong is not only China's second most populous province, but also a neighbor of some provinces with the country's largest rural surplus labor force, including Henan, Jiangsu, and Hebei. As the provincial capital, Jinan is expected to be the destination of growing numbers of rural laborers migrating into cities for employment opportunities. In addition, the development of higher education and high-end services, such as real estate and information technology, is also attracting numerous skilled laborers to the city. Such continued population growth will boost urban development and expansion in the long run.

The Beijing-Shanghai High-Speed Railway, completed in 2011, goes through the west suburban area of Jinan (see Figure 2 - 6), and makes Jinan better connected with the political and economic centers of China. Another east-west running high-speed railway, which connects

Qingdao and Taiyuan via Jinan, is also expected to make transportation between Jinan and central China more convenient. The improved connectivity with other parts of the country is also another opportunity for Jinan's urban development.

**Figure 2 - 6 Jinan West (High-Speed) Railway Station**



*Source: Author*

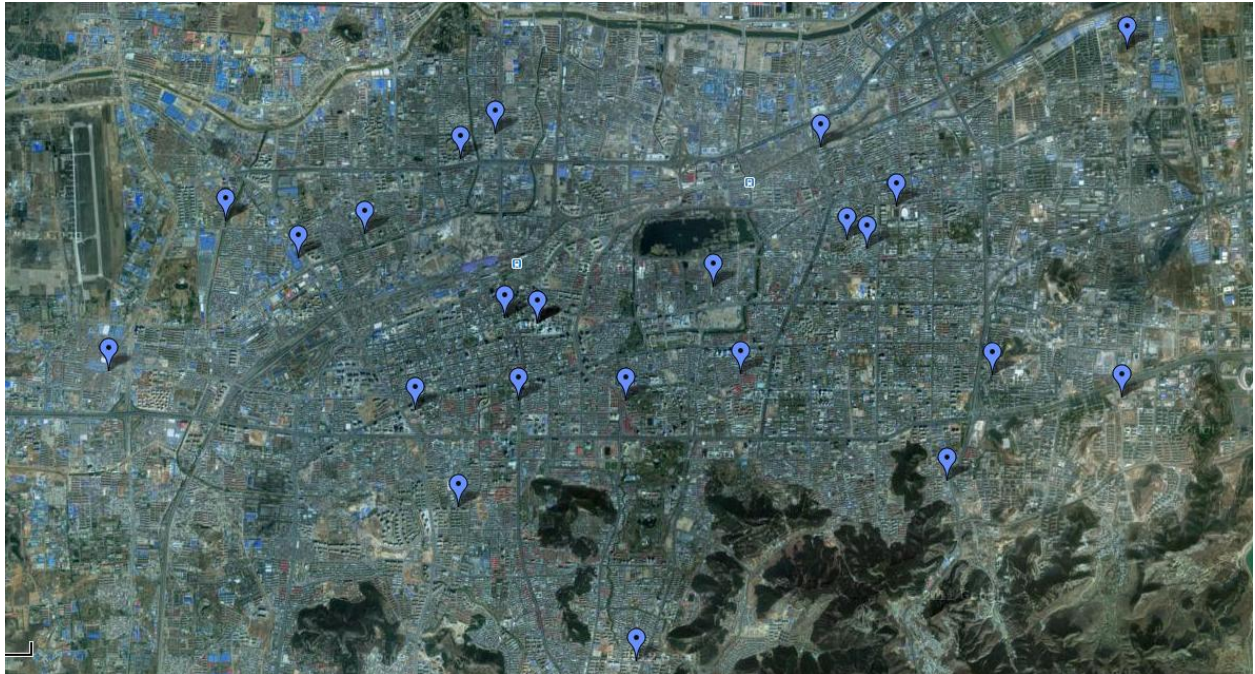
### 2.3 Selected Urban Neighborhoods

The wide range of urban residential neighborhoods in Jinan makes it possible to investigate household operational energy consumption patterns across different urban forms. In this study, a total of 23 urban neighborhoods were selected, representing the four predominant residential neighborhood typologies—traditional, grid, enclave, and superblock (Zhang, 2010; Jiang, 2010). These four typologies represent urban development phases from the pre-1910s to the contemporary era, and collectively cover forms of most urban neighborhoods in Jinan. The other typical urban typology in China, villa (single-family townhouses commonly seen in suburban areas), is not included in the study because of the lack of available data.

The 23 neighborhoods are geographically scattered throughout the city (see Figure 2 - 7), and differ from one another in scale and form. The households residing in these neighborhoods are also diverse in terms of socio-economic status and lifestyle. Such a collection is helpful; a wide range of household and neighborhood characteristics will help to better reveal the connections, if any, between these characteristics and operational energy consumption.



**Figure 2 - 7 Locations of 23 Selected Urban Neighborhoods in Jinan**



*Source: Google Maps, diagrammed by author*

### **2.3.1 Traditional Neighborhoods**

The traditional typology refers to a typical neighborhood style in Jinan's Old City that was built before the 1910s. They are usually non-gated neighborhoods with 2-4 story courtyard buildings, while in some neighborhoods there is also a strong presence of single-story dwellings. The traditional typology is characterized by a compact living environment of high density and shared common facilities, with a main market street passing through the neighborhood (see Figures 2 - 8 and 2 - 9).

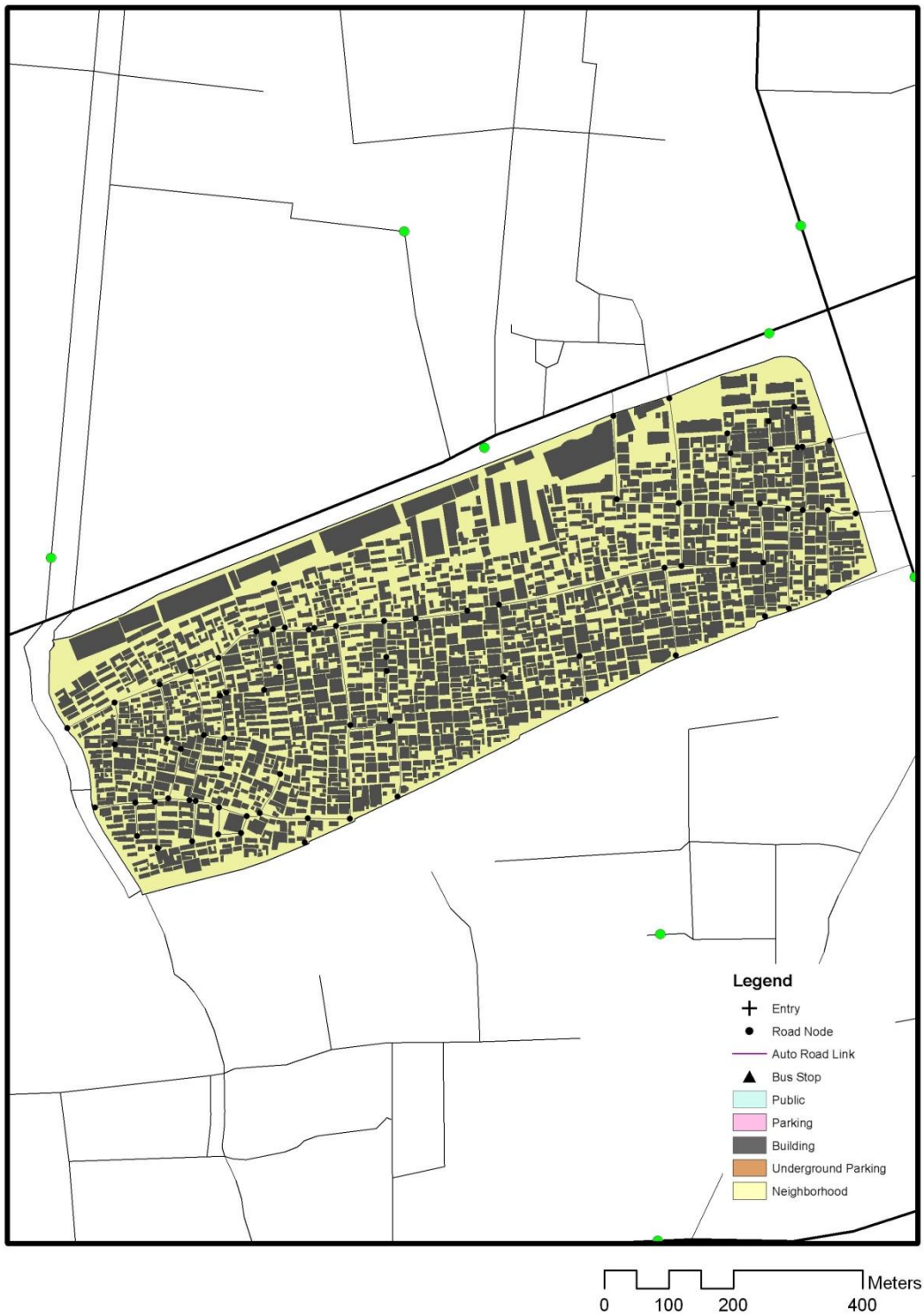


**Figure 2 - 8 Traditional Neighborhood: Furong**



*Source: Author*

**Figure 2 - 9 Traditional Neighborhood Map: Zhang Village**



*Source: Author,  
based on data provided by Beijing Normal University*

Three traditional neighborhoods are included in this study—**Zhang Village, Dikou, and Furong**. Spatially, the traditional neighborhoods are agglomerated in and around Jinan’s central areas, as most of the earliest urban developments in Jinan are concentrated in its historical core. However, the local government and real estate developers have been demolishing many of these traditional neighborhoods, transforming the Old City into an area of commercial office buildings and high-rise residential complexes with higher density and profitability. While demolition and relocation (“chaiqian” in Chinese) of Jinan’s traditional neighborhoods are common, some specifically designated neighborhoods with distinctive historical and cultural values have been protected through conservation efforts.

### 2.3.2 Grid Neighborhoods

Grid typology is a European urban form introduced to Jinan in the early 20th century during its colonial rule under Germany. A grid neighborhood typically consists of several square blocks of approximately 180 meters by 180 meters in size. This typology is characterized by its unique spatial organization of land use.

The grid road system of Jinan is located to the south of its old railway station, and all streets around the area are named with numbers<sup>1</sup> (see Figure 2 - 10). In addition to the grid of main public roads, there are also irregular secondary public accesses, private alleys, and courtyards inside each block.

---

<sup>1</sup> One interesting detail to notice is that the roads’ names around the grid neighborhoods are inconsistent with the common geographical directions—all east-west running roads are named after “longitude”, and all north-south running roads are named after “latitude”. There are multiple explanations to this counter intuitive legend, the most widely believed one of which attributes it to the popular textile industry in historical Jinan. In the Chinese tradition, “longitude” refers to the longer threads while “latitude” refers to the shorter threads in spinning. As the colony in Jinan is a rectangular piece of land of five kilometers east-west by three kilometers north-south, the longer east-west running roads are named by “longitude” while “latitude” has been used to designate the shorter north-south running roads (Jinan Encyclopedia, 2011).



**Figure 2 - 10 Grid Road System in Jinan**



*Source: Bing Maps, diagrammed by author*

This research includes three grid neighborhoods in Jinan—**Commercial District**, **Commercial North**, and **Commercial South**. All three neighborhoods are located around Jinan’s old Commercial Port, which used to be a foreign colony and free trade port between 1904 and 1945 (Jinan Government, 2007). Similar to traditional neighborhoods, the grid neighborhoods in Jinan have been gradually transformed and replaced by new commercial and residential developments.

The structures inside the grid neighborhoods vary greatly, from 2-4 story low-rises to high-rises, including both residential and commercial buildings (see Figures 2 - 11 and 2 - 12). Among all neighborhood typologies in this study, the grid neighborhoods are the most diverse and multi-functional in terms of spatial organization and urban form.

**Figure 2 - 11 Grid Neighborhood: Commercial**



*Source: Author*



Figure 2 - 12 Grid Neighborhood Map: Commercial North



0 50 100 200 300 Meters

Source: Author,  
based on data provided by Beijing Normal University

### 2.3.3 Enclave Neighborhoods

The enclave typology is a popular form of socialist housing from the 1950s to the 1980s. These neighborhoods are usually residential compounds designed for and distributed to the employees of state-owned enterprises and government as welfare. The typical building form of the enclave typology is five to seven-story walk-up apartments (see Figures 2 - 13 and 2 - 14).

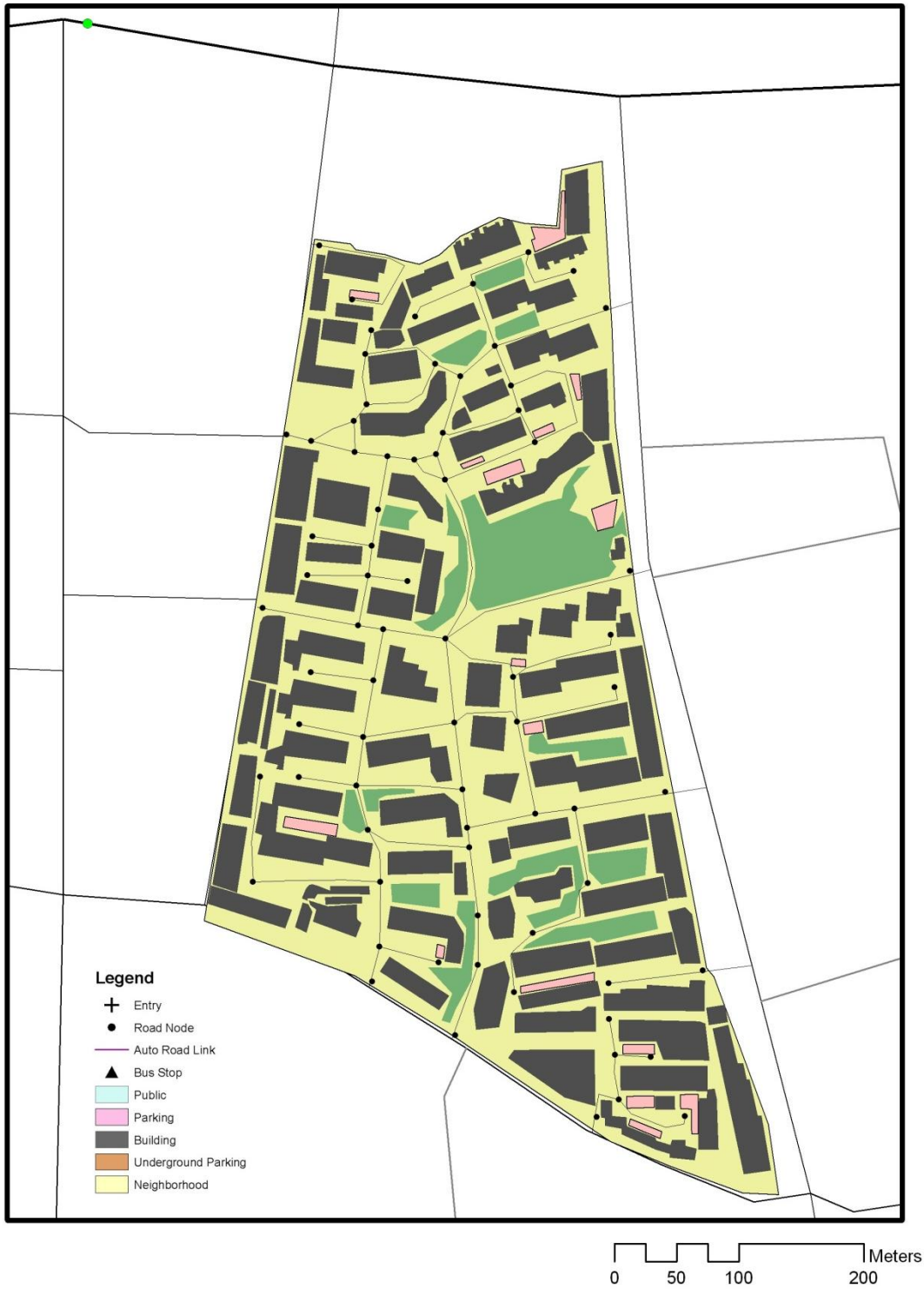
This study includes seven enclave neighborhoods—**Dongcang, Wuyingtian, Foshanyuan, Yanzishan, Gannan, Kuangshan, and Taoyuan**. The enclave neighborhoods in Jinan are mostly located in the immediate periphery around the city center.

**Figure 2 - 13 Enclave Neighborhood: Dongcang**



*Source: Author*

**Figure 2 - 14 Enclave Neighborhood Map: Foshanyuan**



*Source: Author,  
based on data provided by Beijing Normal University*



### 2.3.4 Superblock Neighborhoods

The superblock typology is currently the most popular high-rise pattern among projects of private developers. These neighborhoods are built after the 1990s and are targeted at the newly emerging middle- and upper-class families. Superblocks are typically gated neighborhoods of 20-40 story residential high-rises with large open public space (see Figures 2 - 15 and 2 - 16).

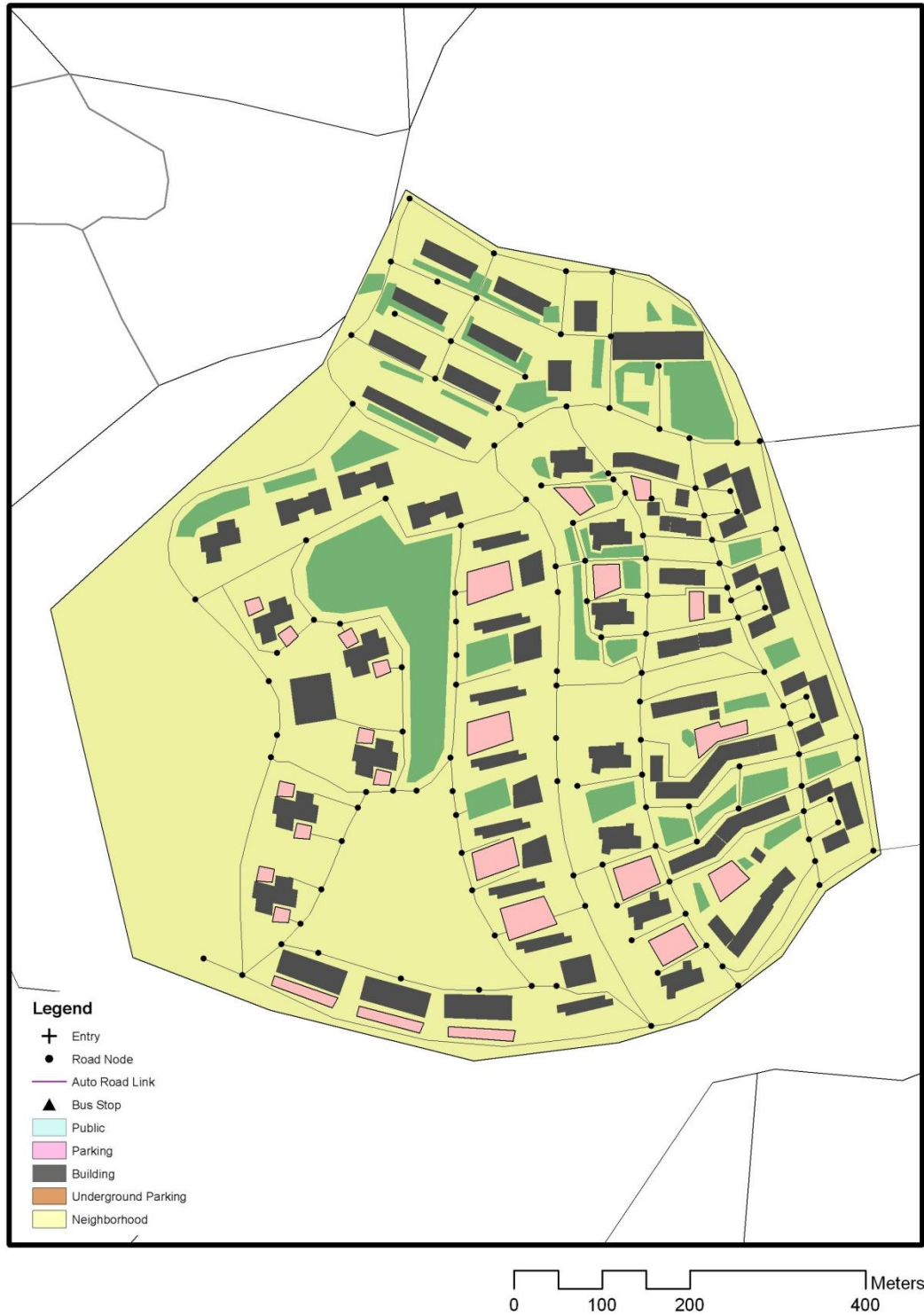
Ten superblock neighborhoods are included in this research: **Lvjingjiayuan, Sunshing100, Shanghai Garden, Jixiangyuan, Mingshi, Weidong, Feicuijun, New World, Quancheng Garden, and Digital Bay**. The superblock neighborhoods have mostly been constructed in peripheral locations in the city after China's land and housing reform of the late 1980s, which granted households certain freedom of housing choice and encouraged home ownership (Huang and Clark, 2002). The superblock neighborhoods, which are mostly "commodity housing" built by real estate developers on land leased by the state, mainly cater to economically affluent home buyers.

**Figure 2 - 15 Superblock Neighborhood: Mingshi**



*Source: Author*

**Figure 2 - 16 Superblock Neighborhood Map: Sunshine 100**



*Source: Author,  
based on data provided by Beijing Normal University*

In this chapter, I have summarized Jinan's key positions as a provincial capital, a regional economic center, a transportation hub, and a city with a historical core and fast growing outskirts. I argue that Jinan is a good case to analyze household operational energy consumption in the Chinese urban setting because of its moderate urban scale, representative climate pattern, diverse neighborhood typologies, and thriving development opportunities. I conclude this chapter by introducing the 23 urban neighborhoods that have been included in this study, categorizing them into four typologies—traditional, grid, enclave, and superblock.

In Chapter 3, I will further illustrate the analytical framework, present the data cleaning and processing specifics, and introduce the quantitative research method of this research.

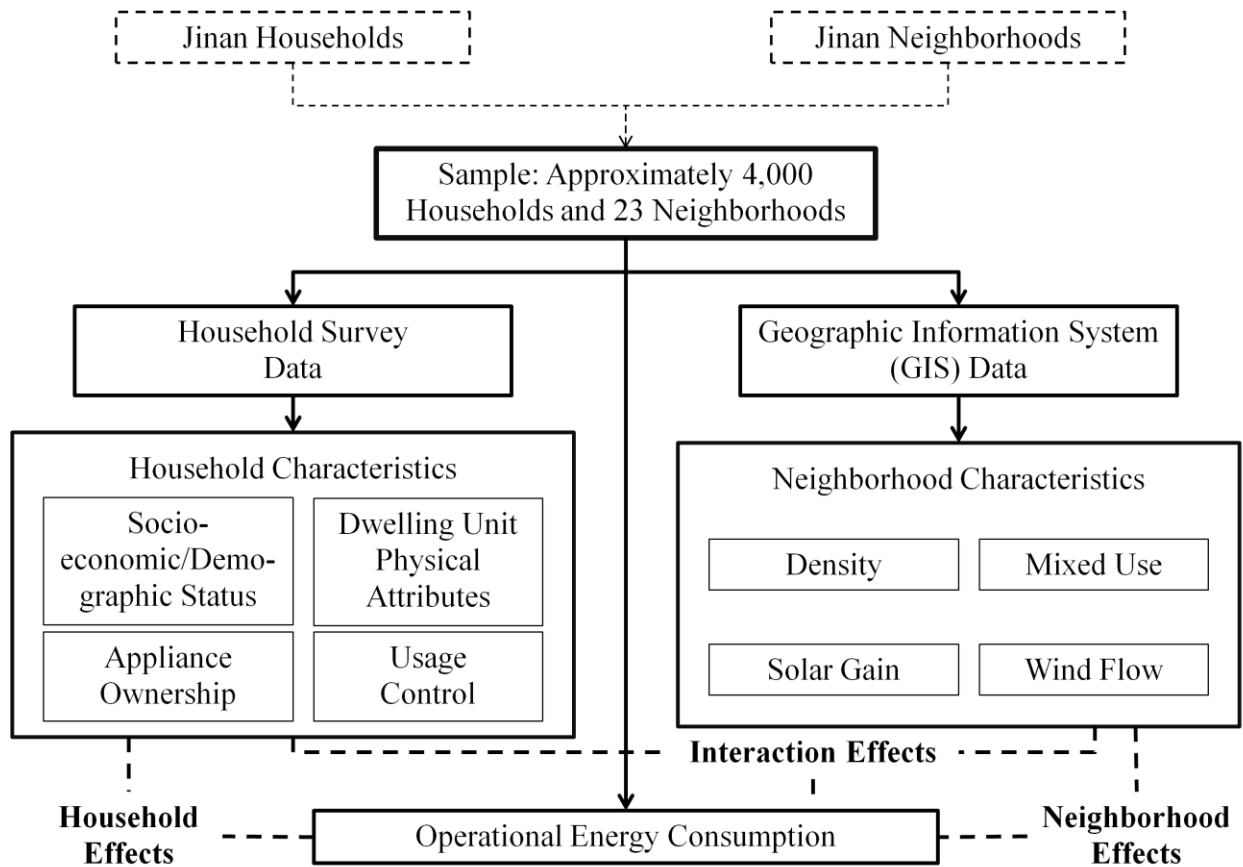
## Chapter 3: Data and Methods

Based on the household survey responses and geographic information of the selected Jinan neighborhoods, I will present the analytical framework of this research in this chapter. I will first introduce the data employed in this study, and discuss the collection, initial processing and analysis of the information. Then, I will further explain the methodological framework of this research, illustrating how the research questions can be addressed and answered by the empirical evidence collected from Jinan.

### 3.1 Data

The data framework for the quantitative analysis in this thesis is summarized in Figure 3 - 1. This research is mainly built upon two sets of data sources—household survey responses and neighborhood geographic information system (GIS) analysis. As part of “Making the Clean Energy City in China” project, both sets of data are based on a sample of approximately 4,000 households from 23 urban neighborhoods. The operational energy consumption data are estimated based on the self-reported household utility bills and dwelling construction areas, the household characteristics are obtained through the household survey, and the neighborhood characteristics are summarized from the GIS data. The three bolded texts in the framework chart represent the key questions this research aims to solve: the household, neighborhood, and interaction effects on operational energy consumption in urban China.

**Figure 3 - 1 Data Framework**



*Source: Author*

As mentioned, the household characteristics come from the “Jinan Urban Residents’ Residential and Passenger Transport Energy Consumption Survey”, which was completed over two consecutive years by Shandong University. The first round of survey was conducted in the summer of 2009 and interviewed approximately 2,700 households in nine neighborhoods; the second round survey was completed in 2010, and covered approximately 1,300 households in 14 neighborhoods. The pre-selected neighborhoods, covering all four urban neighborhood typologies, formed the sampling frame, within which surveyed households were selected based on simple random sampling. Only adults aged between 20 and 65 were eligible respondents, and in the households with two or more eligible respondents, the individual who had the most recent birthday was chosen to finish the survey. The participation in the survey was voluntary, and the questionnaires were written in Chinese. After the survey, Shandong University was in charge of data input and the initial cleaning of the data sets.

The household survey data provide key information on selected household characteristics that may influence operational energy consumption. The characteristics included in this study are socio-economic and demographic status, dwelling physical attributes, appliance ownership, and usage control. The specifics of these variables will be further discussed in Chapter 5. In addition, the survey contained information—reported utility bills and dwelling unit areas—from which household operational energy consumption is calculated. The specific calculation equations will be further discussed in Chapter 4.

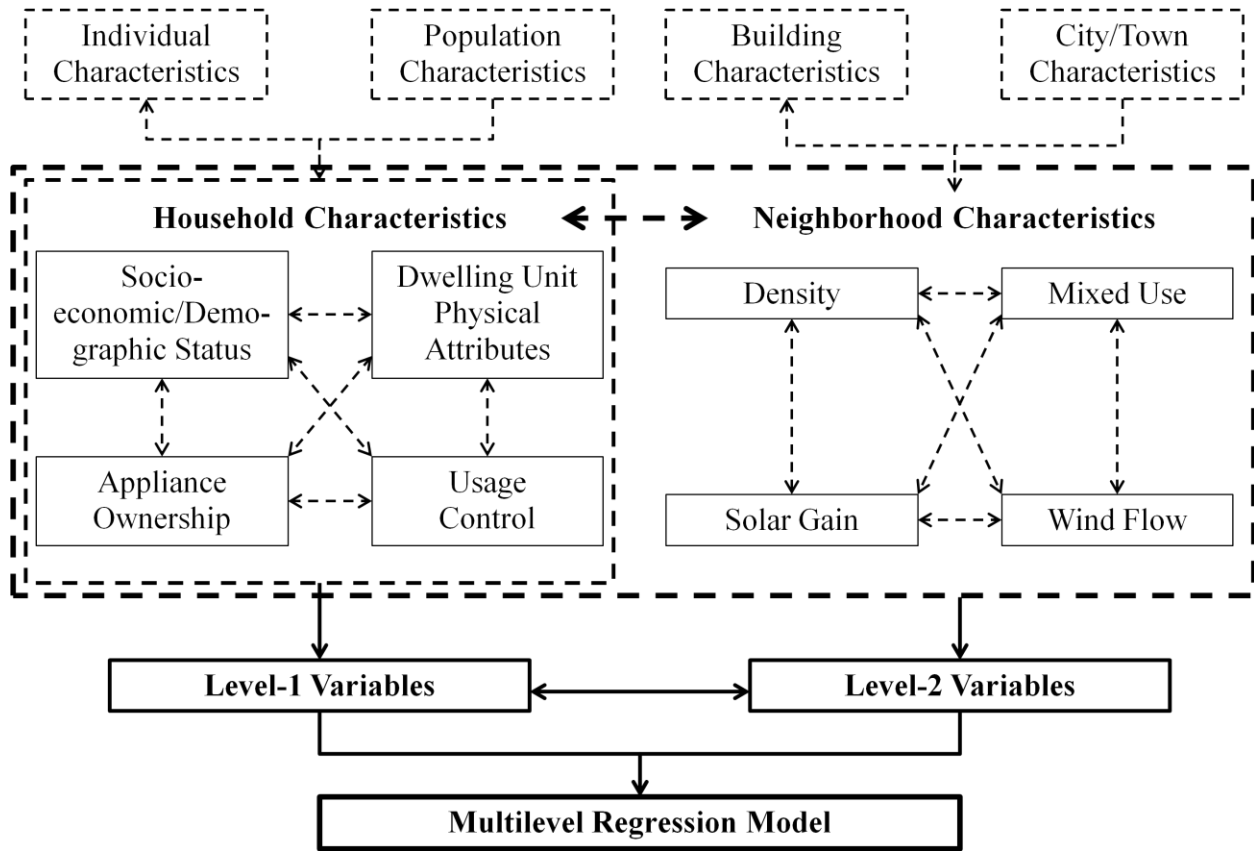
Due to coordination difficulties, the questionnaires used over the two years were slightly different. Several key categories in the two versions of the questionnaires covered different information. For example, the 2009 survey asked respondents to provide ownership information on air conditioners, refrigerator, televisions, desktop computers, and solar water heaters; however, the 2010 survey only asked about air conditioners and solar water heaters. The two sets of questions on households' attitudes towards energy saving behaviors also differed in wording and content. For this study, such inconsistency reduces the total number of variables that can be feasibly included in the quantitative analysis models.

The physical characteristics of the 23 Jinan neighborhoods come from GIS data. The GIS analysis was initially conducted by Beijing Normal University, and includes spatial information of the neighborhood boundaries as well as the major residential and commercial buildings, green and other public grounds, parking spaces, motorways and pedestrian paths, and public transportation stops. Four groups of neighborhood variables, including indicators on density, mixed use, solar gain, and wind flow, are further calculated from these GIS data. The specifics of the neighborhood-level data will be presented in Chapter 6.

### **3.2 Method**

The methodological framework of this thesis is presented in Figure 3 - 2. Households are on a level between the scales of individual household members and the general population, while the neighborhood characteristics are situated on a scale between a single building and the entire city or town. Such medium-level scales of variables are helpful for capturing both micro- and macro-level information.

**Figure 3 - 2 Methodological Framework**



*Source: Author*

As the households are sorted and grouped according to the neighborhood they reside in, the household characteristics are embedded in the neighborhood characteristics. The household and neighborhood characteristics mutually connect and interact, so do the variables within these two categories.

In the multilevel regression model, the lower-level household characteristics are treated as Level-1 variables and the higher-level neighborhood characteristics are inputted as Level-2 variables. The multilevel analysis can reveal the household, neighborhood, and interaction effects on operational energy consumption; these specifics will be discussed in Chapter 7.



## **Chapter 4: Overview of Household Operational Energy Consumption**

In this chapter, I will introduce the four major energy sources included in this study, explain the calculation methods for energy consumption data in detail, and present an overview of household operational energy consumption in all surveyed neighborhoods. The foundation of this study rests on comprehensive and accurate data on the operational energy consumption of Jinan households. However, due to the limitations of data availability and survey methods, I have to estimate household energy consumption mostly from self-reported data on utility bills.

I will subsequently compare household operational energy consumption data with those of common area, transportation, and embodied energy consumption, and provide a broad picture of energy consumption patterns in Chinese households. To test if such estimated energy use data faithfully represents actual operational energy consumption behavior, I will also assess the validity of the method by comparing the energy estimates derived from the self-reported data with actual energy consumption data provided for a subset of Jinan households.

### **4.1 Calculation of Operational Energy Consumption**

The operational energy consumption of Jinan households can mostly be traced to four major sources—electricity, natural gas, coal, and centralized heating (see Table 4 - 1). Each energy source has a distinctive usage ratio depending on specific household and neighborhood characteristics. I define usage ratio as the percentage of households that use the particular energy source. A household may not utilize a particular energy source either because that energy source is unavailable in the neighborhood—for example, the lack of centralized heating system in many old neighborhoods—or because the household can choose another energy source as a replacement—for example, the ownership and usage of electric stoves can substitute for natural gas consumption.

**Table 4 - 1 Major Operational Energy Sources of Surveyed Neighborhoods**

<b>Energy Source</b>	<b>Usage</b>	<b>Usage Ratio*</b>
<b>Electricity</b>	Electrical appliances (air conditioner, television, computer, light, etc.), space heating	100.00%
<b>Natural Gas</b>	Cooking, water heating	75.46%
<b>Coal</b>	Space heating, cooking, water heating	16.15%
<b>Centralized Heating</b>	Space heating	60.16%

\* Usage ratio is defined as the percentage of households that use the energy source.

*Data Source: Author*

In this section, I build estimations upon survey data acquired from households in typical Jinan neighborhoods, and transform household utility bills and physical attributes of their residential units into energy consumption data through set of equations.

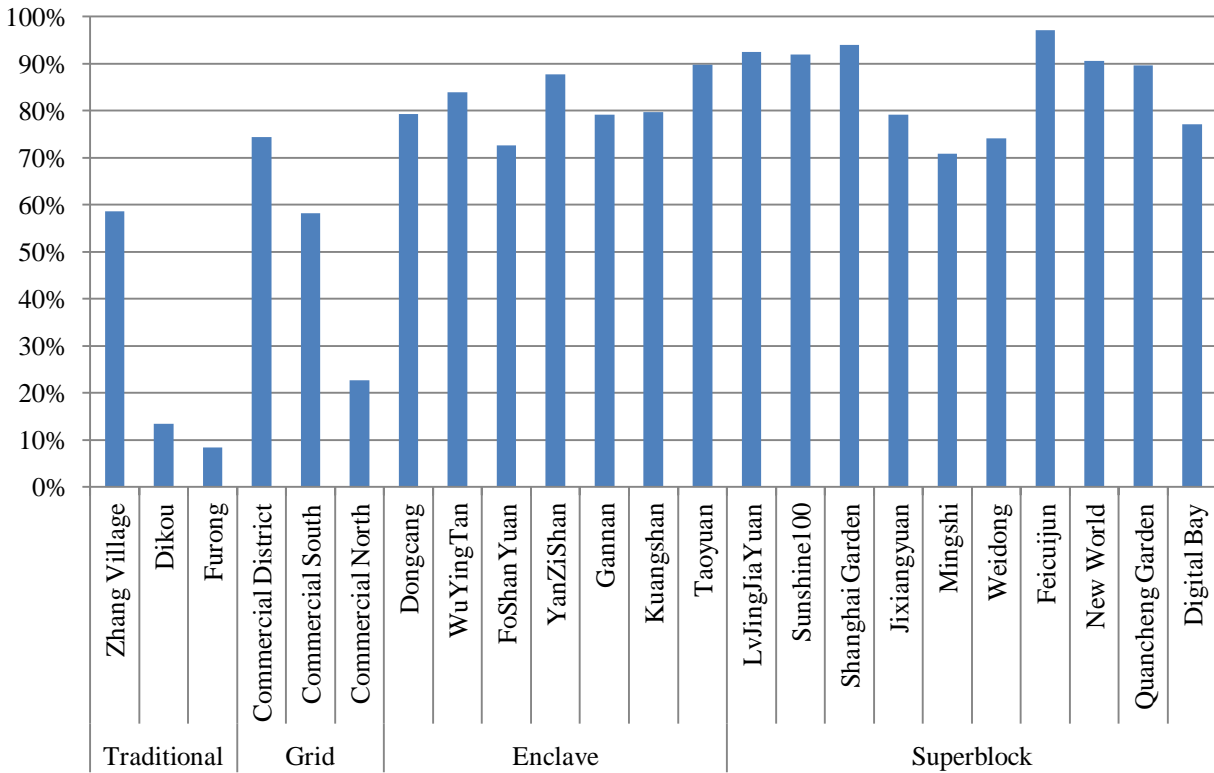
#### **4.1.1 Usage Ratios of Major Energy Sources**

All surveyed households in this study have access to electricity. For a typical Jinan (and most urban Chinese) household, electricity is the major source for operational energy consumption, supporting use of common electrical appliances, including air conditioner, television, computer, and lights. In addition, electric heating is also commonly used in units where centralized heating is not available, or households find additional heating appliances necessary or desirable.

Natural gas is utilized by three-quarters of all households covered in the survey. To many Jinan households, natural gas is the primary source for cooking and water heating. However, the natural gas usage ratio varies greatly across different neighborhood typologies—the enclave and superblock neighborhoods have average coverage ratios of over 80% while Dikou and Furong, the two traditional neighborhoods, have extremely low coverage at around 10%. The direct transmission of natural gas requires pipelines and compressor stations; therefore, the enclave and superblock neighborhoods, whose buildings have been designed and constructed more recently, have higher natural gas coverage than the traditional and grid neighborhoods (see Figure 4 - 1). In the neighborhoods that do not have natural gas pipelines, households can only choose to

purchase liquefied gas stored in steel bottles. Such inconvenience likely greatly discourages natural gas usage ratios in some traditional and grid neighborhoods.

**Figure 4 - 1 Natural Gas Usage Ratios of Surveyed Neighborhoods**



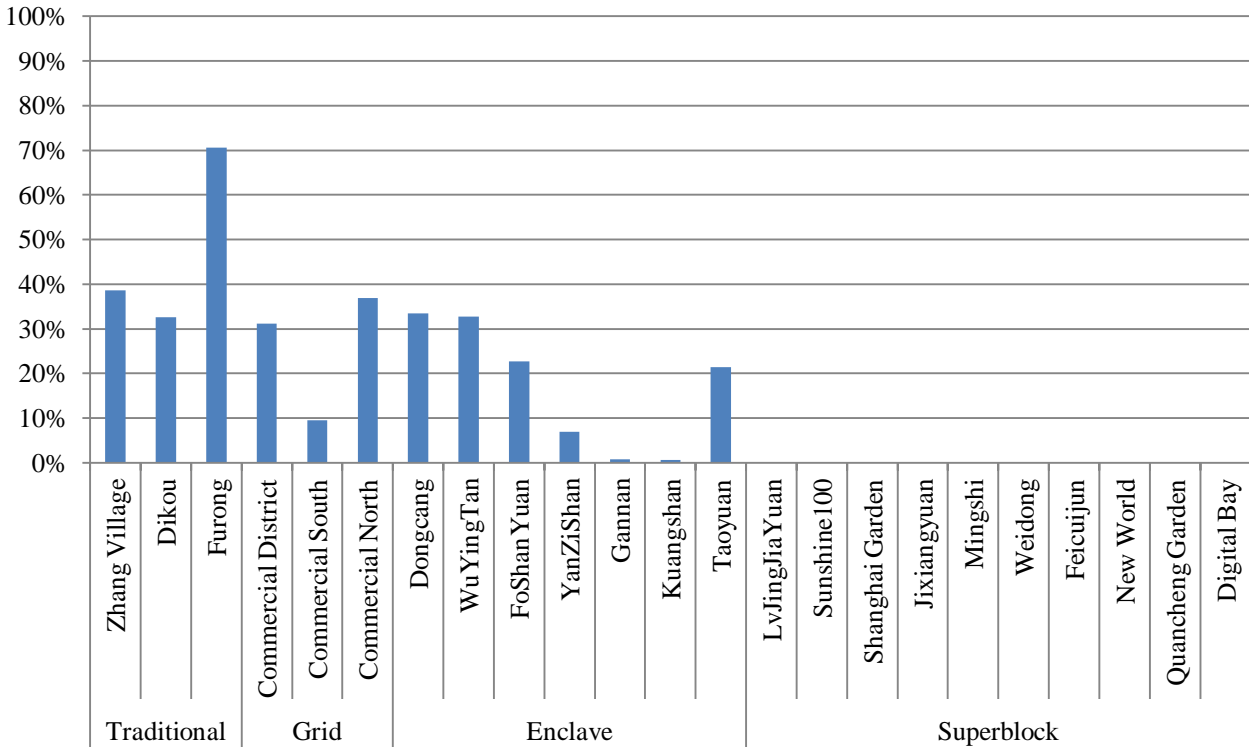
Neighborhood	Usage Ratio
<b>Traditional</b>	38.98%
<b>Grid</b>	57.99%
<b>Enclave</b>	81.34%
<b>Superblock</b>	88.45%

*Source: Author*

Coal used to be a common operational energy source for cooking and heating in Chinese households, but the introduction of pipeline natural gas and centralized heating systems and the rising awareness of coal’s environmental and safety hazards have made coal usage less appealing. Nowadays, households in the traditional neighborhoods are the primary users of coal because

natural gas and centralized heating systems are often absent in their dwellings. On the contrary, the physical design and property management schemes of superblock neighborhoods have prevented the usage of coal in the high-rise residential buildings (see Figure 4-2).

**Figure 4 - 2 Coal Usage Ratios of Surveyed Neighborhoods**



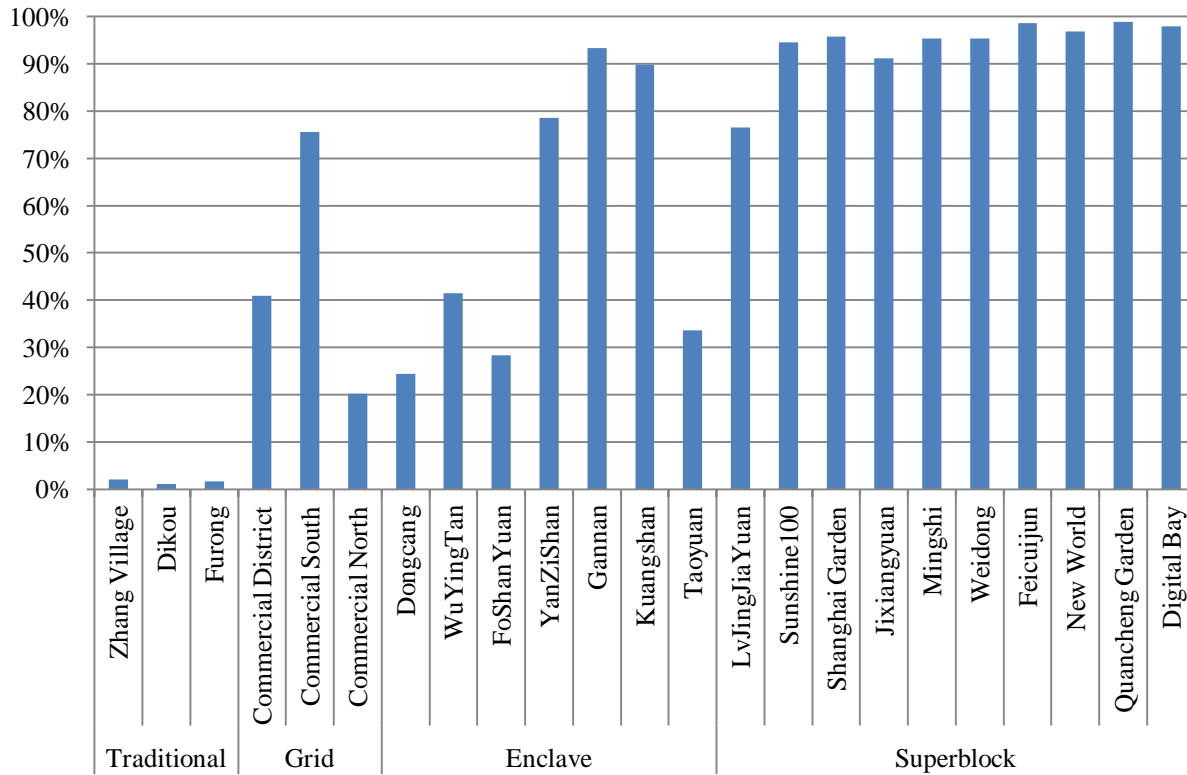
Neighborhood	Usage Ratio
<b>Traditional</b>	45.08%
<b>Grid</b>	27.46%
<b>Enclave</b>	18.52%
<b>Superblock</b>	0.00%

*Source: Author*

Similar to natural gas, centralized heating coverage also highly depends on the presence of transmission networks. The building codes in northern China require the availability of centralized heating in newly constructed residential neighborhoods, and the remodeling of some of Jinan’s older neighborhoods has also included installing centralized heating systems in those

residential buildings. Still, some traditional, grid and enclave neighborhoods are not well covered by centralized heating (see Figure 4 - 3).

**Figure 4 - 3 Centralized Heating Usage Ratios of Surveyed Neighborhoods**



Neighborhood	Usage Ratio
<b>Traditional</b>	1.77%
<b>Grid</b>	44.06%
<b>Enclave</b>	52.95%
<b>Superblock</b>	92.85%

Source: Author

### 4.1.2 Calculation of Electricity Consumption

As mentioned, the calculation of household electricity consumption is based on households' self-reported data from their electricity utility bills. As Jinan has a climate pattern with four distinct seasons, the household electricity bills are expected to fluctuate throughout the year. The household average monthly electricity bill is thus calculated as the weighted average of household electricity bills in representative spring/fall, summer, and winter months.<sup>2</sup>

Jinan's electricity is mostly generated from coal-fired power plants; therefore, the calculation traces electricity consumption back to coal as the primary energy source and takes energy conversion and transmission losses into consideration. The equation to calculate household electricity energy consumption is presented as Equation 4-1:

$$EMJ = \frac{EBILL \cdot 12}{EPRICE} \cdot q_E \div (1 - \beta) \div \varepsilon \quad (4-1)$$

Symbol	Description	Value	Unit
EMJ	Household annual electricity energy consumption		MJ
EBILL	Household average monthly electricity bill		Yuan
EPRICE	Electricity price	0.5469	Yuan/KWH
q <sub>E</sub>	Thermal-electricity conversion factor	3.6	MJ/KWH
β	Electricity transmission loss rate	7.08%	
ε	Coal power plant conversion rate	35.47%	

*Source: Zhang, 2010*

### 4.1.3 Calculation of Gas Consumption

Jinan households typically consume one of the following three types of gases: liquefied natural gas (LNG), liquefied petroleum gas (LPG), and coal gas. The calculation of gas consumption is based on the reported average monthly gas bill and the type of natural gas the household uses.

<sup>2</sup> A typical year in Jinan consists of three months in spring, summer, fall and winter respectively and there is no apparent difference in household electricity consumption between spring and fall. Therefore, based on Jinan's climate pattern, the household average monthly electricity bill is calculated by summing 50% of spring/fall monthly bill, 25% of summer monthly bill and 25% of winter monthly bill.

The estimated gas energy consumption includes both the heat natural gas produces and the incomplete combustion losses. Equation 4-2 explains the calculation methods in detail:

$$GMJ = \frac{GBILL \cdot 12}{GPRICE} \cdot \gamma_G \quad (4-2)$$

Symbol	Description	Value	Unit
<b>GMJ</b>	Household annual natural gas energy consumption		MJ
<b>GBILL</b>	Household average monthly gas bill		Yuan
<b>GPRICE</b>	LNG unit price	2.4	Yuan/m <sup>3</sup>
	LPG unit price	13.9	Yuan/m <sup>3</sup>
	Coal gas unit price	1.3	Yuan/m <sup>3</sup>
<b><math>\gamma_G</math></b>	LNG unit thermal value	36.4	MJ/m <sup>3</sup>
	LPG unit thermal value	118.2	MJ/m <sup>3</sup>
	Coal gas unit thermal value	16.74	MJ/m <sup>3</sup>

*Source: Zhang, 2010*

#### 4.1.4 Calculation of Coal Consumption

Though not used at all by the superbloc households, coal is still an important cooking and heating energy source for many living in some of the traditional, grid, and enclave neighborhoods (see Figure 4 - 2). The calculation of coal consumption is also based on the self-reported monthly consumption of coal by surveyed households. Similar to the calculation of gas consumption, Equation 4-3 estimates total coal consumption, including both the actual heat it generates and the losses due to incomplete combustion process.

$$CMJ = \frac{CBILL \cdot 12}{CPRICE} \cdot \gamma_C \quad (4-3)$$

Symbol	Description	Value	Unit
CMJ	Household annual coal energy consumption		MJ
CBILL	Household annual coal bill		Yuan
CPRICE	Coal unit price	876	Yuan/ton
$\gamma_C$	Coal unit thermal value	26,700	MJ/ton

*Source: Zhang, 2010*

#### 4.1.5 Calculation of Centralized Heating

When available, centralized heating is uniformly provided to each household through a centralized system in each residential neighborhood or building. In almost all such residential buildings in urban China, there are no individual control units. As a result, households are not able to switch on or off centralized heating in their dwellings on their own, nor can they adjust the heating temperature. In Jinan, government mandate requires that centralized heating is provided for 140 days per year in residential units, lasting from November 5th to March 15th. The heating fees for each household are calculated based on the households' unit area and are collected at the beginning of every heating season.

Centralized heating, similar to electricity, is generated by coal power plants and provided through steam or hot water in a tinned radiator. As there is no indoor usage control units for centralized heating, its energy consumption can be best estimated based on the construction area of each home unit. The estimation captures the total amount of energy consumption generated in the process of heating provision to households, including the estimated losses in the heating power plant conversion and pipeline transmission (see Equation 4-4).



$$\text{CHMJ} = 86.4 \cdot \text{AREA} \cdot \text{N} \cdot q_{\text{CH}} \cdot \frac{t_i - t_a}{t_i - t_{o,h}} \div \mu_b \div \mu_p \div 1000 \quad (4-4)$$

Symbol	Description	Value	Unit
<b>AREA</b>	Unit construction area		m <sup>2</sup>
<b>N</b>	Heating period	140	day
<b>q<sub>CH</sub></b>	Building heating index	33.16	W/m <sup>2</sup>
<b>t<sub>i</sub></b>	Indoor designed temperature during heating period	18	°C
<b>t<sub>a</sub></b>	Average outdoor temperature during heating period	-0.9	°C
<b>t<sub>o,h</sub></b>	Outdoor designed temperature during heating period	-7	°C
<b>μ<sub>b</sub></b>	Cogeneration boiler efficiency	0.87	
<b>μ<sub>p</sub></b>	Pipe network efficiency	0.98	

*Source: Zhang, 2010*

## 4.2 Operational Energy Consumption Patterns

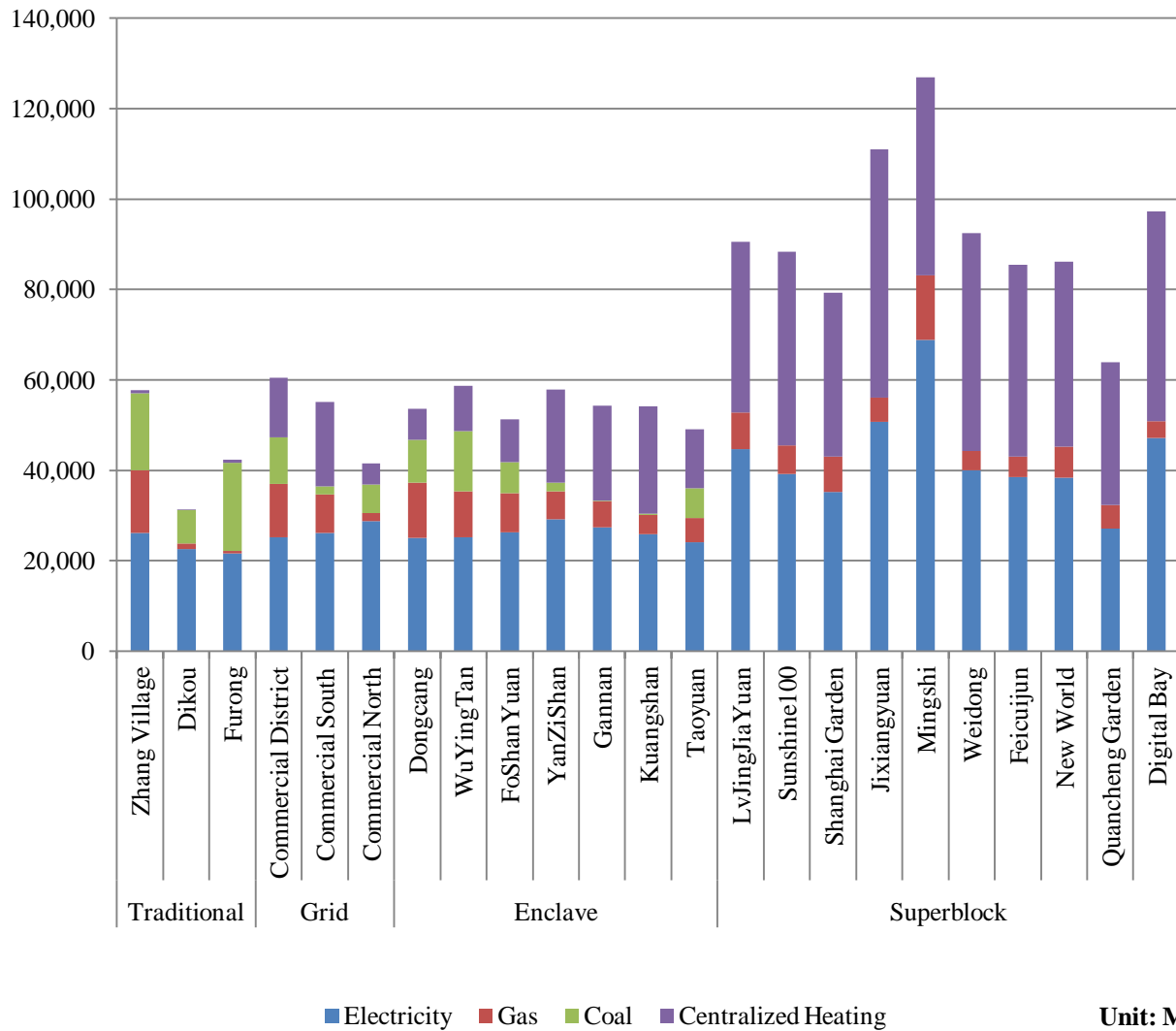
I apply the calculation equations to the survey data collected from the 23 Jinan neighborhoods, and estimate operational energy consumption patterns. Both the amount and source of operational energy consumption vary greatly across the respondents, indicating that operational energy consumption may be influenced by household and neighborhood characteristics.

Again, the notion of operational energy consumption in this paper only covers the portion of in-home energy consumption of surveyed Jinan residents. Common area energy consumption of the neighborhoods, together with transportation and embodied energy consumption data, will be compared in the next section.

### 4.2.1 Energy Consumption Amount

Based on the equations introduced in the previous section, I calculate the total operational energy consumption of the approximately 4,000 surveyed households. Figure 4 - 4 summarizes the average annual energy consumption per household by energy source in the 23 neighborhoods.

**Figure 4 - 4 Annual Per Household Operational Energy Consumption Amounts  
By Energy Source of Surveyed Neighborhoods**

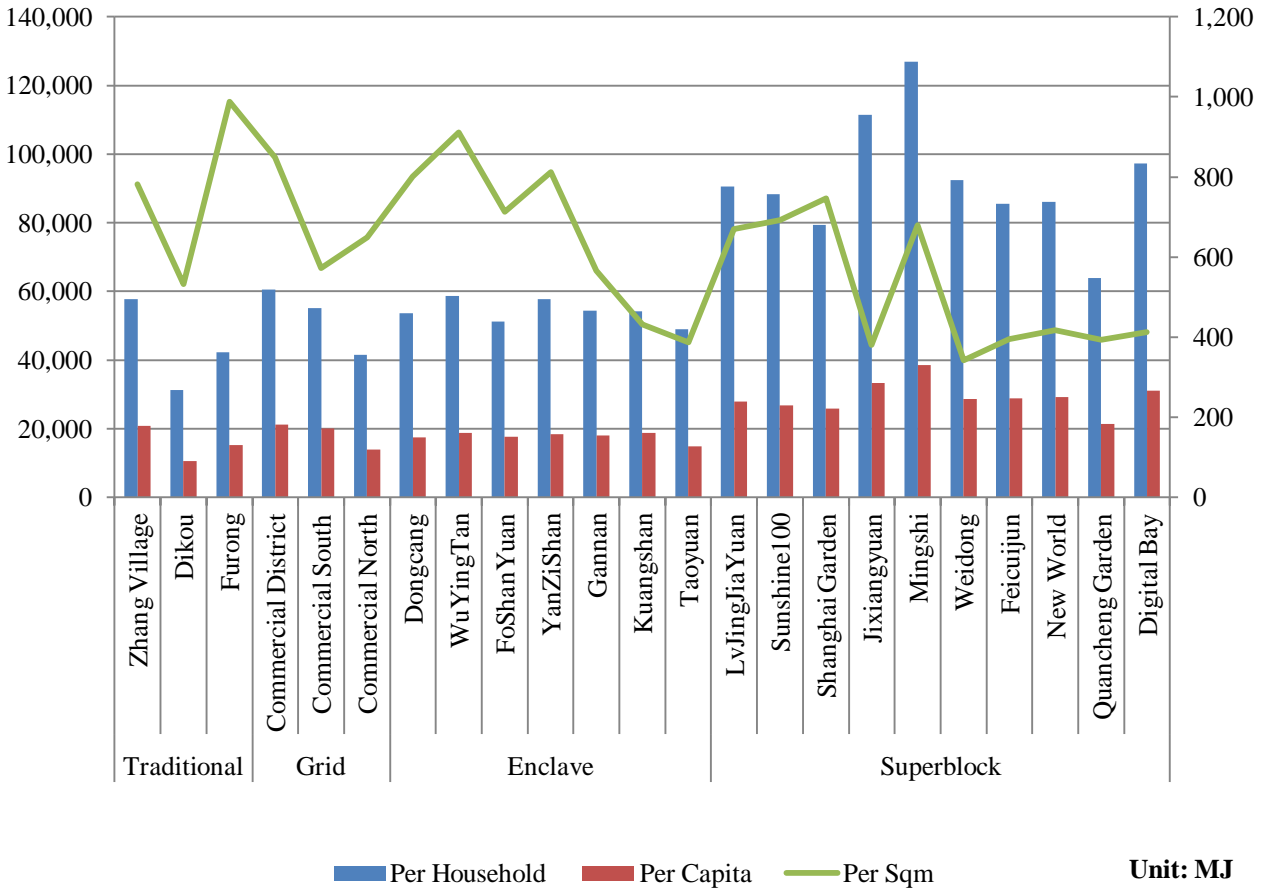


Neighborhood	Electricity	Gas	Coal	Centralized Heating
<b>Traditional</b>	24,483	8,543	15,915	535
<b>Grid</b>	26,243	8,592	7,398	12,368
<b>Enclave</b>	26,333	8,090	5,899	14,270
<b>Superblock</b>	40,495	6,861	0	40,559

Source: Author

Figure 4 - 5 shows per household, per capita, and per square meter annual operational energy consumption in the 23 neighborhoods surveyed in this study. Superblocks consume much more energy, approximately 40% to 50% more, compared to the other three types of neighborhoods on a per household basis. The difference between the enclave and the grid neighborhoods is not obvious. The traditional neighborhoods consume the least operational energy among all neighborhood types.

**Figure 4 - 5 Annual Per Household, Per Capita, and Per Square Meter Operational Energy Consumption in Surveyed Neighborhoods**



Neighborhood	Per Household	Per Capita	Per Sqm
<b>Traditional</b>	49,476	17,671	773
<b>Grid</b>	54,600	19,047	741
<b>Enclave</b>	54,592	17,910	694
<b>Superblock</b>	87,942	27,811	577

*Source: Author*

On a per square meter basis, however, the consumption pattern is reversed. The superblocks consume slightly less energy per square meter than the grid and enclave neighborhoods, and the traditional neighborhoods consume the highest per square meter. This is caused by the larger unit area of the superblock neighborhoods—even though superblock households consume higher

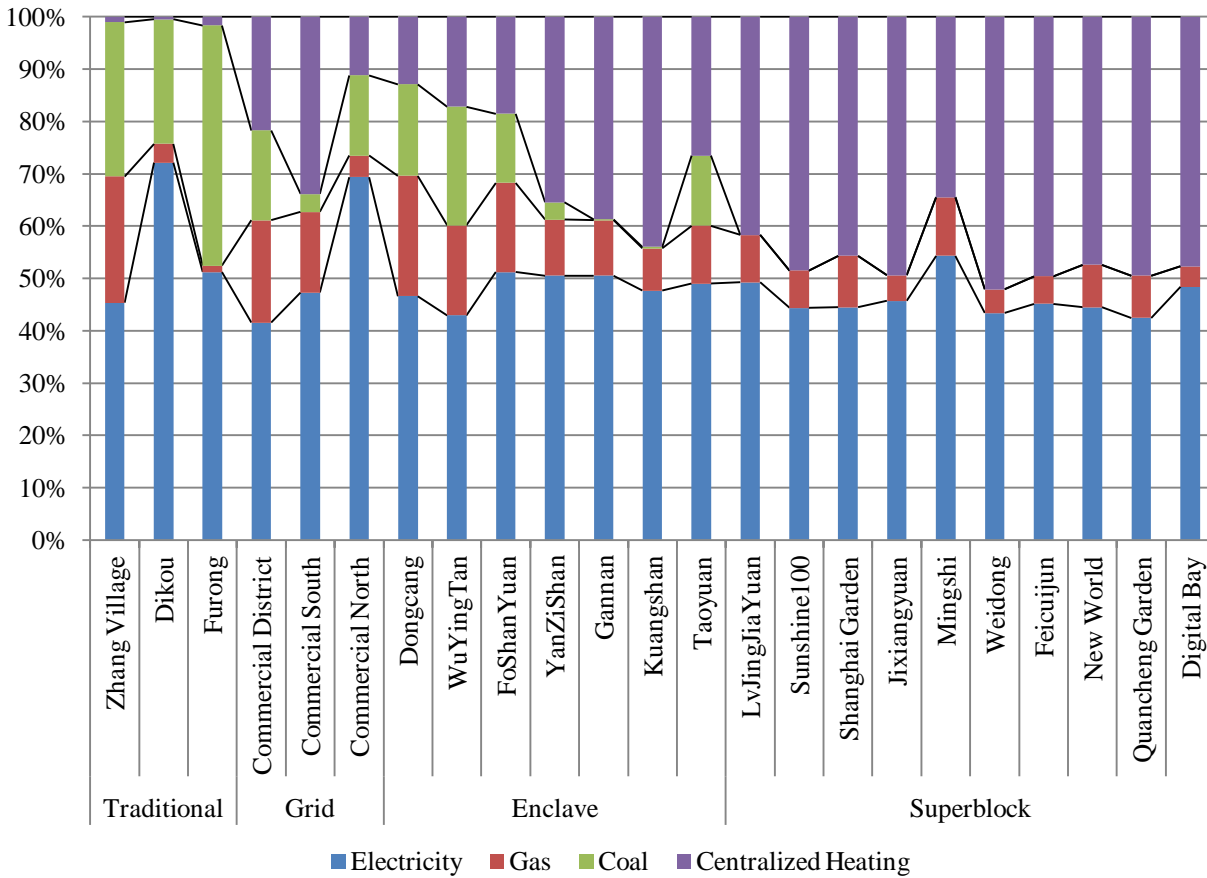
amount of operational energy than those living in the other three typologies, this difference disappears once accounting for dwelling unit size.

#### **4.2.2 Energy Consumption Share**

Figure 4 - 6 shows operational energy consumption shares by energy source. Again, the differences in energy source shares imply that energy consumption behavior may be influenced by the different household and neighborhood characteristics of Jinan residents.

The consumption share of electricity is generally consistent in all types of neighborhoods, accounting for slightly less than 50% of total energy consumption. In the superblock neighborhoods, consumption of coal is completely absent. The dominant energy sources are electricity and centralized heating, each accounting for almost half of the total energy consumption. In the enclave and grid neighborhoods, the household energy source choices are more diverse. Coal is widely used for space heating purposes in neighborhoods where centralized heating is not available. In the traditional typology, very few households can access centralized heating so coal consumption completely takes over. Compared to the consumption of centralized heating and coal, the consumption share of gas is more stable at around 10%, with the share in the enclave and grid neighborhoods slightly higher than in the other two types of neighborhoods.

**Figure 4 - 6 Annual Operational Energy Consumption Shares  
By Energy Source of Surveyed Neighborhoods**



Neighborhood	Electricity	Gas	Coal	Centralized Heating
<b>Traditional</b>	49.48%	17.27%	32.17%	1.08%
<b>Grid</b>	48.06%	15.74%	13.55%	22.65%
<b>Enclave</b>	48.24%	14.82%	10.80%	26.14%
<b>Superblock</b>	46.06%	7.80%	0.00%	46.13%

*Source: Author*

A key finding is that the existence of centralized heating system apparently determines the patterns of household energy consumption shares of the neighborhoods. The energy source of those neighborhoods that have complete centralized heating systems, including all of the superblock neighborhoods, is primarily evenly shared between electricity and centralized heating.

Some of the grid and enclave neighborhoods that have only partial centralized heating systems consume more coal and natural gas as substitutes for heating energy sources. Coal accounts for a large proportion (27.59%) of the energy consumption in the traditional neighborhoods, where most households have no access to centralized heating.

### **4.3 Operational vs. Common Area, Transportation, and Embodied Energy Consumption Patterns**

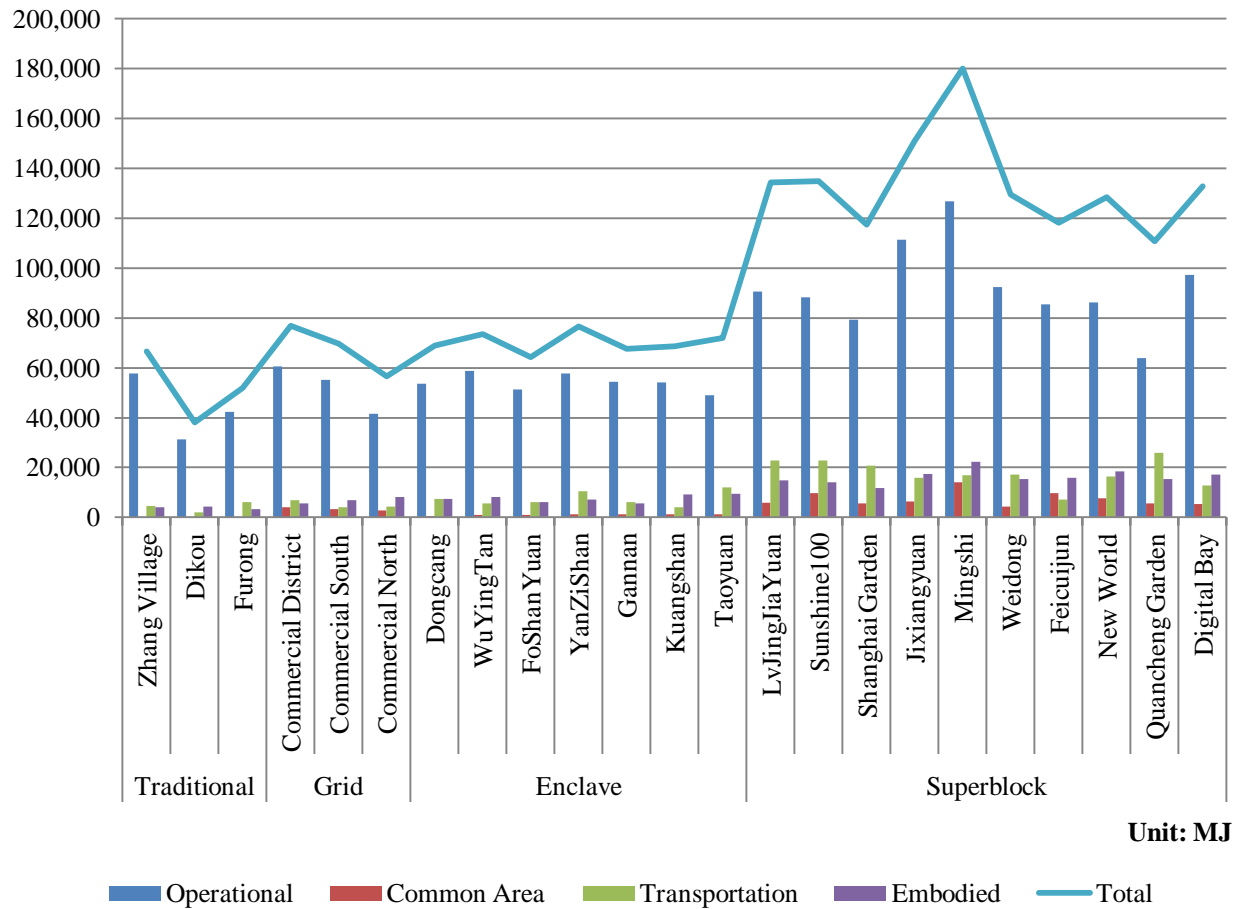
To present a broader picture of neighborhood energy consumption in Jinan residential neighborhoods, I compare the operational energy consumption with the common area, transportation, and embodied energy consumption data.

The common area energy consumption is calculated through a series of equations which estimate energy use for water pumps, public lighting, elevators, access security, and underground parking based on physical attributes and total population of the neighborhoods. The transportation energy consumption is estimated based on weekly travel behavior documented in the household survey, and accounts for both travel distances and modes of the household members. The embodied energy consumption captures the estimated energy consumed in the construction process of the neighborhoods. These energy consumption data come from “Making the Clean Energy City in China” Project’s Second Year Report (Making the Clean Energy City in China, 2012).

#### **4.3.1 Energy Consumption Amount**

Figure 4 - 7 illustrates that the total energy consumption amounts of all surveyed neighborhoods in Jinan generally follow the patterns indicated in their operational energy consumption amounts. The superblock neighborhoods still consume exceptionally higher amounts of energy compared to the other typologies with an annual consumption of 130,463 MJ on average per household. The traditional neighborhoods remain the least energy consuming on a per household basis, consuming on average less than half of the superblock households’ total energy. The total energy consumption amounts of the grid and enclave remain in the middle again.

**Figure 4 - 7 Annual Per Household Operational, Common Area, Transportation, and Embodied Energy Consumption Amounts of Surveyed Neighborhoods**



Unit: MJ

Neighborhood	Operational	Common Area	Transportation	Embodied	Total
<b>Traditional</b>	49,476	310	4,518	3,901	58,206
<b>Grid</b>	54,600	3,546	5,617	6,503	70,266
<b>Enclave</b>	54,592	1,029	7,357	7,440	70,418
<b>Superblock</b>	87,942	7,200	20,238	15,082	130,463

Source: Author

More specifically, the trends prevail in each of the energy consumption categories. Due to the presence of high energy-consuming common area facilities, higher automobile ownership ratios, and the higher energy intensity of constructing high-rise buildings, the superblock neighborhoods



are highest in common area, transportation, and embodied energy consumption categories. The traditional typology consumes the least amount of energy in all categories while the grid and enclave neighborhoods are placed in between.

The variation in energy use in common areas and embodied in construction can be partially explained by physical attributes, as the construction and operation of low- and mid-rises are much less energy intensive than high-rise buildings. The lower common area energy consumption can also be attributed to that fact that large energy consumers such as underground parking spaces and elevators are usually absent in the three non-superblock typologies. In terms of transportation, many of the traditional, grid, and enclave neighborhoods are located closer to the city center, and the residents are more inclined to walk, ride bicycles, or take public transportation, which observably reduces energy consumption compared to the usage of cars.

#### **4.3.2 Energy Consumption Share**

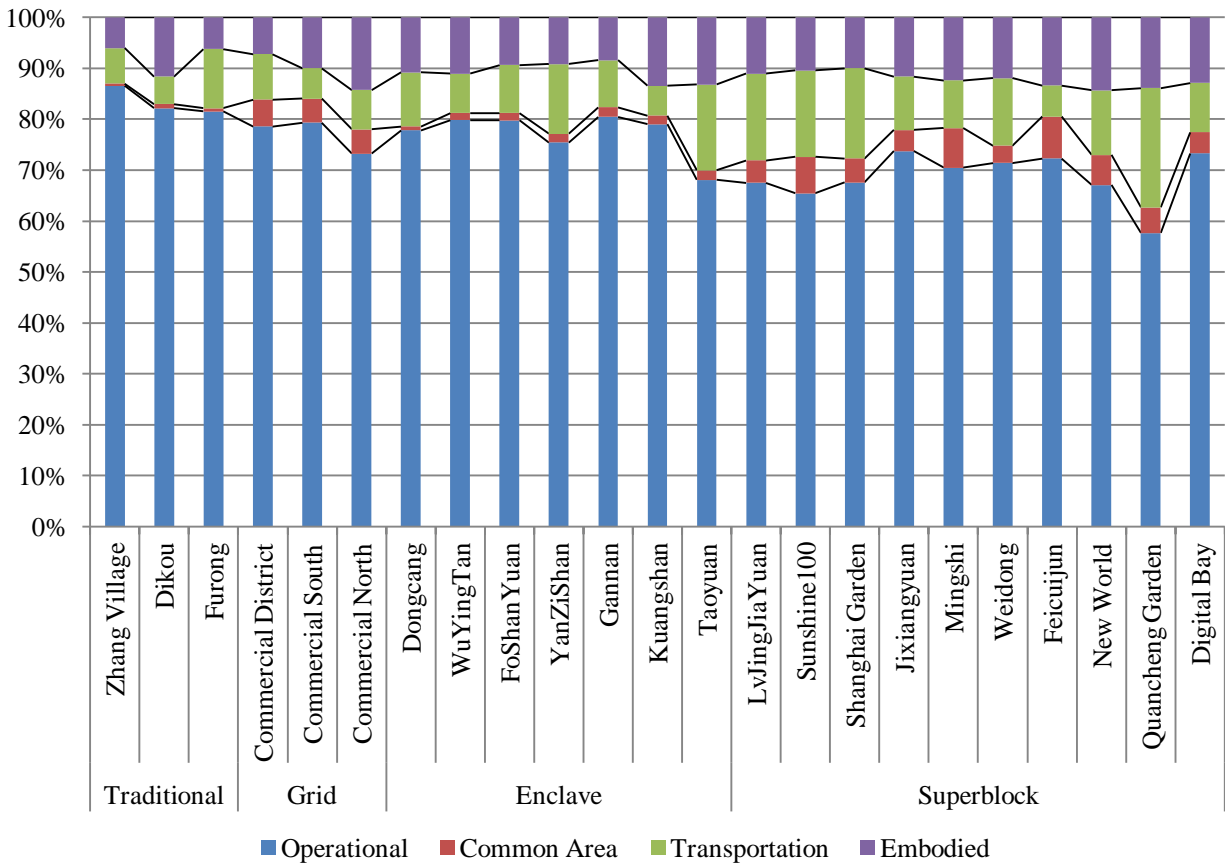
The shares of operational, common area, transportation, and embodied energy consumption generally remain consistent across all surveyed neighborhoods. Operational energy consumption accounts for roughly three quarters of the total household energy consumption and is the largest portion among the four categories across all neighborhoods (see Figure 4 - 8). Transportation and embodied energy consumption both take up approximately 10% of the total energy consumption, on average, and common area energy consumption constitutes the smallest share.

The large share of operational energy usage indicates that in-home activities are still the major causes of energy consumption, implying a large possibility to reduce residential energy consumption by increasing operational energy efficiency in the residential sector. Even though vehicle ownership has been steadily growing in urban China, transportation has not yet become a major contributor to total energy consumption of Chinese households. However, transportation energy consumption is expected to grow dramatically if automobile ownership continues to rise, thus focusing on operational energy efficiency does not mean we can ignore measures to contain growth in household transportation energy consumption.

It is important to note the potential trade-off relationship between operational and transportation energy consumption data. Households who spend more time outdoors and traveling more often by high energy-consumption modes such as automobiles may consume larger shares of energy in

transportation while the portion of operational energy consumption may become smaller, and vice versa. Such a trade-off is reflected in this study, as the households in the traditional, grid, and enclave neighborhoods spend a much smaller portion of energy consumption on transportation compared to the superblock residents, many of whom commute to work and/or travel for leisure by car.

**Figure 4 - 8 Annual Total Energy Consumption Shares of Surveyed Neighborhoods**



Neighborhood	Operational	Common Area	Transportation	Embodied
<b>Traditional</b>	85.00%	0.53%	7.76%	6.70%
<b>Grid</b>	77.70%	5.05%	7.99%	9.25%
<b>Enclave</b>	77.53%	1.46%	10.45%	10.57%
<b>Superblock</b>	67.41%	5.52%	15.51%	11.56%

Source: Author

The common area, transportation, and embodied energy consumption all generally follow the pattern of operational energy consumption across the surveyed neighborhoods. In addition, operational energy consumption constitutes a predominant portion of the total energy consumption. Therefore, although focused only on operational energy consumption, this study can also shed some light on the total energy consumption patterns and behaviors of Jinan households.

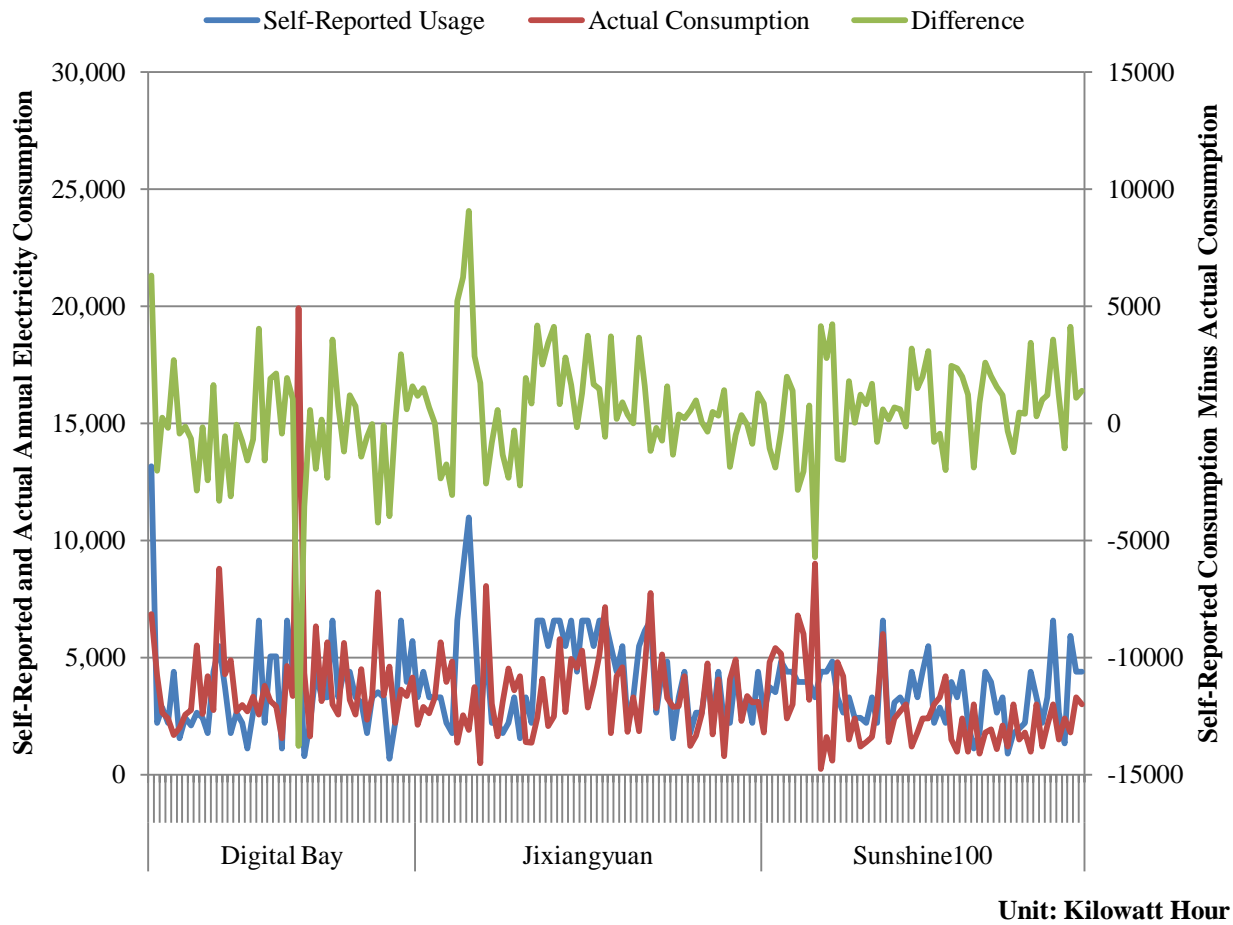
#### **4.4 Self-Reported Utility Data vs. Actual Energy Consumption**

Before moving on to discussing the connections between operational energy consumption and household and neighborhood characteristics, it is important to attempt to validate the estimations of operational energy consumption data in this section.

As discussed, the operational energy consumption calculations in this study are based on self-reported data of utility bills and unit construction areas. If the surveyed households have not provided accurate estimates of their actual utility bills, the calculated energy consumption could be inaccurate. To examine if the self-reported data faithfully reflect actual energy consumption, three neighborhoods covered in this study were selected to verify the self-reported electricity utility bills with the actual electricity consumption data.

The study has gathered annual total electricity consumption data from three superblock neighborhoods: Sunshine100, Jixiangyuan, and Digital Bay. The data come from monitoring devices installed by Jinan's local electricity supply authority and accurately reflect the annual electricity consumption in kilowatt hours of the households covered in the survey. Figure 4 - 9 shows the differences between the self-reported-based estimates and the actual data of electricity consumption. A paired t-test with a significance level of 0.05 further suggests that in Sunshine100 and Jixiangyuan, the self-reported data are higher than the actual electricity consumption while no statistically significant difference can be found in Digital Bay.

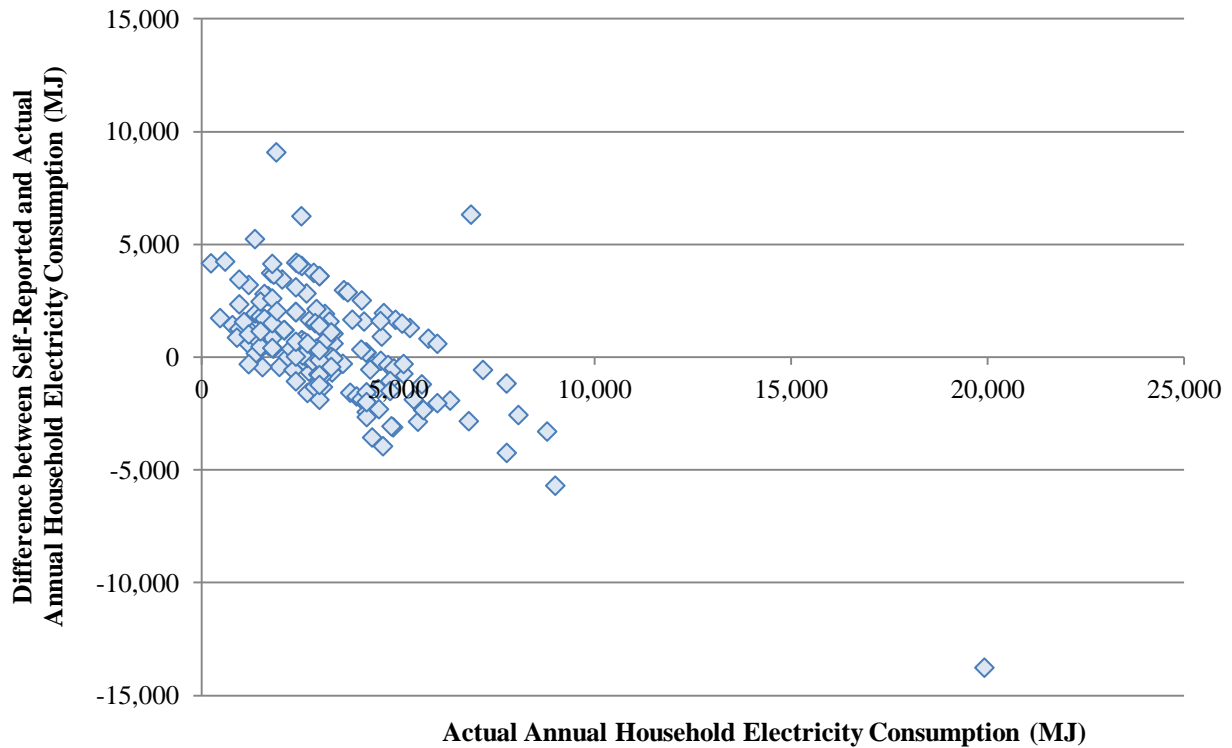
**Figure 4 - 9 Self-Reported and Actual Annual Electricity Consumption of Selected Neighborhoods**



*Source: Author*

More careful scrutiny of the data suggests a consistent distribution pattern of the differences between the self-reported and the actual electricity consumption data. Households with lower annual electricity consumption are more likely to over-report usage in their estimates while households who consume more electricity tend to under-report their utility bills. This is indicated in Figure 4 - 10 which shows that the differences between the self-reported and the actual data have a negative correlation with the actual electricity consumption amount. One possible explanation of this phenomenon is that households tend to form inaccurate impressions of their electricity consumption behavior, and falsely believe their utility bills are closer to an average level.

**Figure 4 - 10 Distribution Patterns of Differences between Self-Reported and Actual Electricity Consumption Data**



*Source: Author*

The results suggest that the self-reported data may not be accurate proxies of the actual electricity consumption. However, due to the limited availability of the actual energy consumption data in Jinan, the self-reported utility bills are the only feasible option to yield household energy consumption estimations and to conduct the following analyses for this study. The estimated energy consumption data calculated in this chapter will be utilized to analyze the relationships between household and neighborhood characteristics and operational energy consumption. Meanwhile, it is important to bear in mind that the usage of these biased data instead of the actual energy consumption data is one deficiency of this study.

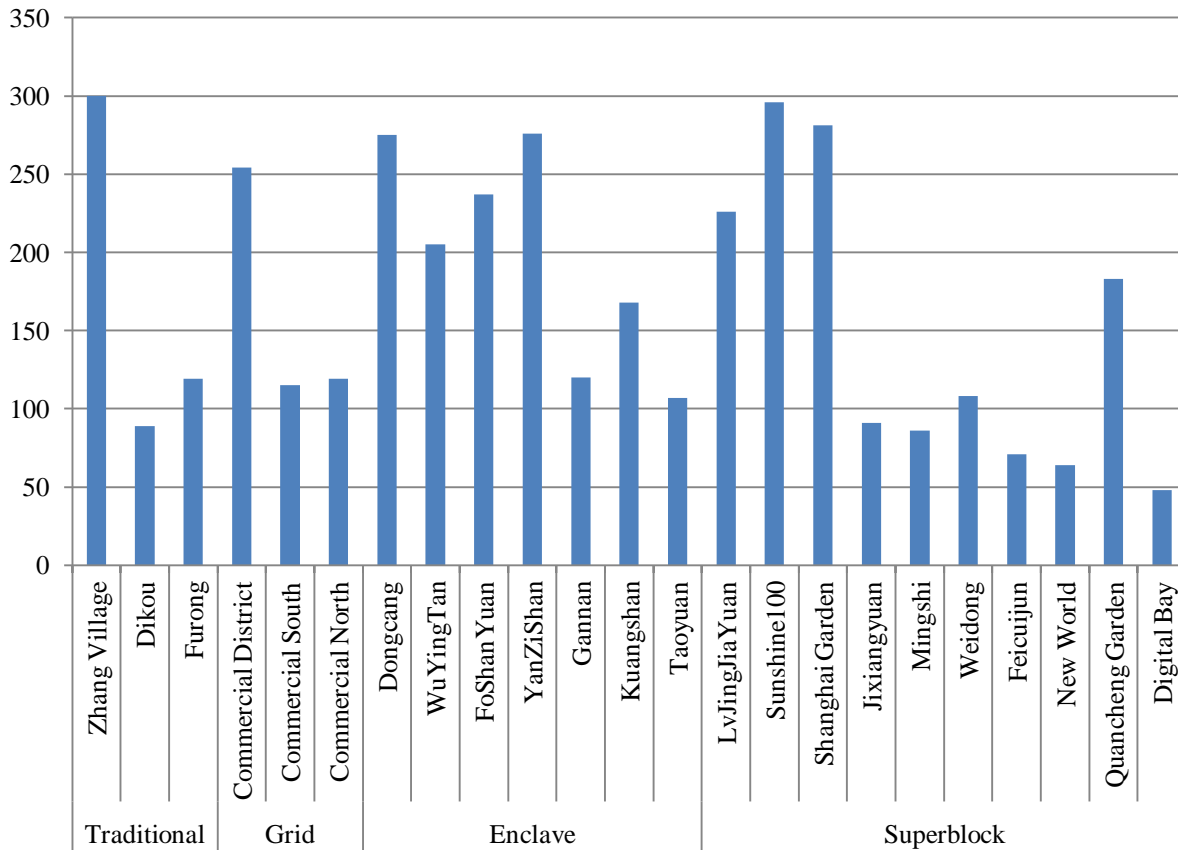
## **Chapter 5: Household Characteristics and Operational Energy Consumption**

In this chapter, I conduct descriptive analysis of the survey data to examine associations between operational energy consumption patterns and household characteristics. I first summarize all key household information acquired through the survey and categorize them into four groups reflecting different aspects of household characteristics—socio-economic and demographic status, physical attributes of the dwelling, appliance ownership, and usage control. Then, I present the results and findings from the descriptive statistics to compare and analyze the household characteristics across different neighborhoods. I conclude this chapter by illustrating the relationships between selected household characteristics and operational energy consumption.

### **5.1 Household Survey Data**

As mentioned previously, a total of 3,831 valid household observations from 23 Jinan neighborhoods can be extracted from the survey over the two years; although the average numbers of households surveyed per neighborhood is around 165 households, considerable variation in the number of surveyed households exists across the typologies (see Figure 5 - 1).

**Figure 5 - 1 Number of Households Surveyed in Surveyed Neighborhoods**



Neighborhood	Total Number of Households Surveyed	Average Number of Households Surveyed per Neighborhood
<b>Traditional</b>	508	169
<b>Grid</b>	488	163
<b>Enclave</b>	1388	198
<b>Superblock</b>	1447	145

*Source: Author*

In addition to the figures on household operational energy consumption, which are either directly calculated from their self-reported utilities bills (electricity, gas, and coal) or indirectly estimated from their dwellings' physical attributes (centralized heating) as indicated in Chapter 4, the survey also acquired background information on individual households in four basic categories:

- **Socio-economic and demographic status:** household income, household size, household structure, and homeownership;
- **Dwelling physical attributes:** unit area and whether or not it is located on the top floor;
- **Appliance ownership:** air conditioner and solar water heater;
- **Usage control:** whether or not the household uses electric heating.<sup>3</sup>

## 5.2 Overview of Household Characteristics

The survey data reveal that household characteristics vary significantly across different neighborhood typologies. The traditional and superblock neighborhoods represent the two opposite extremes in almost all measurements of household characteristics, while the grid and enclave neighborhoods lie in the middle.

### 5.2.1 Socio-Demographic Status

Household income, household size, and home ownership all vary greatly among the four typologies, especially between the traditional and superblock neighborhoods.

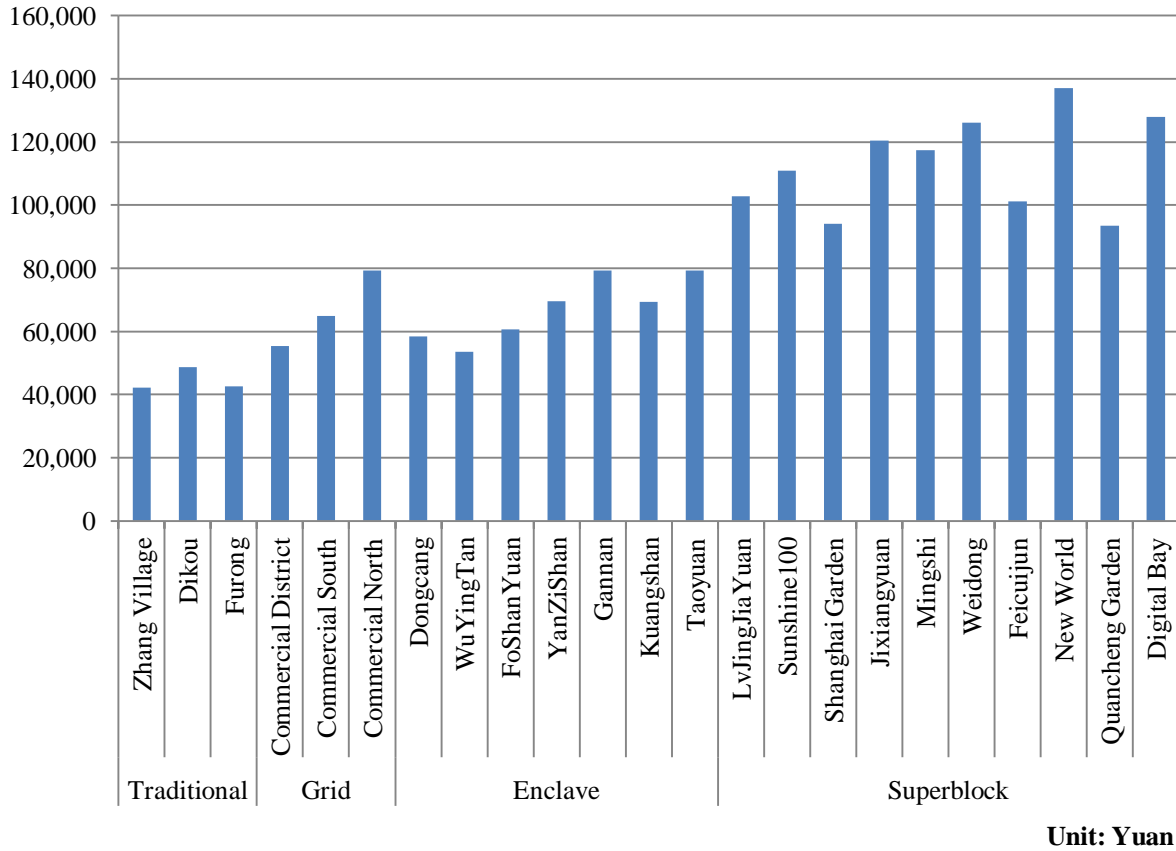
Household income displays a striking picture of the significant inequality of income distribution among Jinan residents (see Figure 5 - 2). Income level varies significantly across neighborhood typologies. The households living in traditional neighborhoods (44,450 yuan/year) earn less than 40% on average of those who live in the superblocks (107,568 yuan/year). This indicates the difference of economic status of residents in those two groups of neighborhoods—many traditional neighborhood residents are retired pensioners and migrant blue-collar workers while most superblock neighborhood residents are much more affluent who can afford the more expensive “commodity housing” built by private real estate developers. The average annual household incomes of those living in the grid and enclave neighborhoods are in between the superblock and traditional, at around 64,000 yuan.

---

<sup>3</sup> Centralized heating is not metered in China, and in this research, its energy consumption is estimated based on unit size. Unit size will be included as an independent variable in the multilevel regression model; therefore, I exclude centralized heating from the total operational energy consumption in the multilevel analysis in Chapter 7. I include electric heating in this research as a “usage control” variable in order to examine whether the presence of electric heating significantly impacts the non-centralized heating energy consumption in the subsequent multilevel analysis.



**Figure 5 - 2 Annual Household Incomes of Surveyed Neighborhoods**

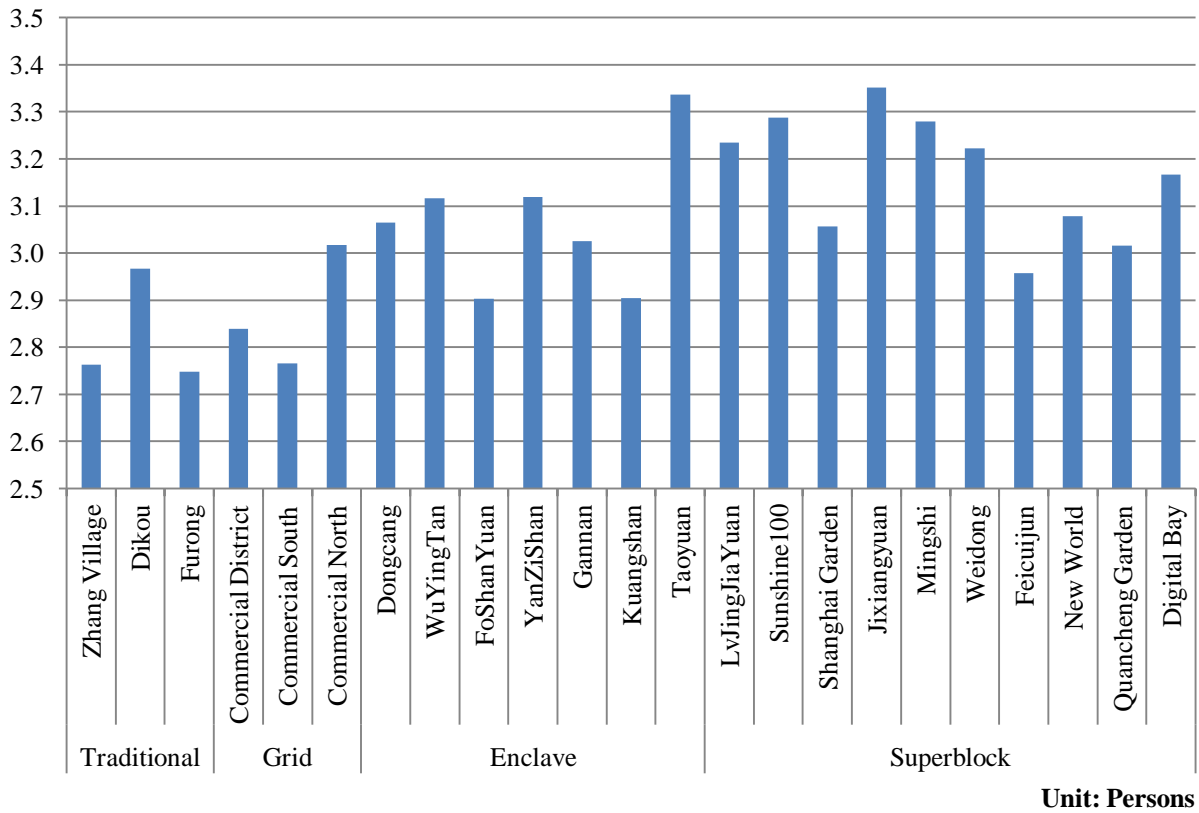


Neighborhood	Average Annual Household Income
<b>Traditional</b>	43,450
<b>Grid</b>	63,480
<b>Enclave</b>	65,038
<b>Superblock</b>	107,568

*Source: Author*

Due to the country’s family planning policy, massive internal migration (rural to urban), and the transformation of cultural values and lifestyles, China’s traditional notion of “big family” has been greatly challenged, and the smaller nuclear family structure is increasingly the norm. The survey in this study reveals that the average household size of the 23 Jinan neighborhoods is around 3 people (see Figure 5 - 3).

**Figure 5 - 3 Average Household Sizes of Surveyed Neighborhoods**



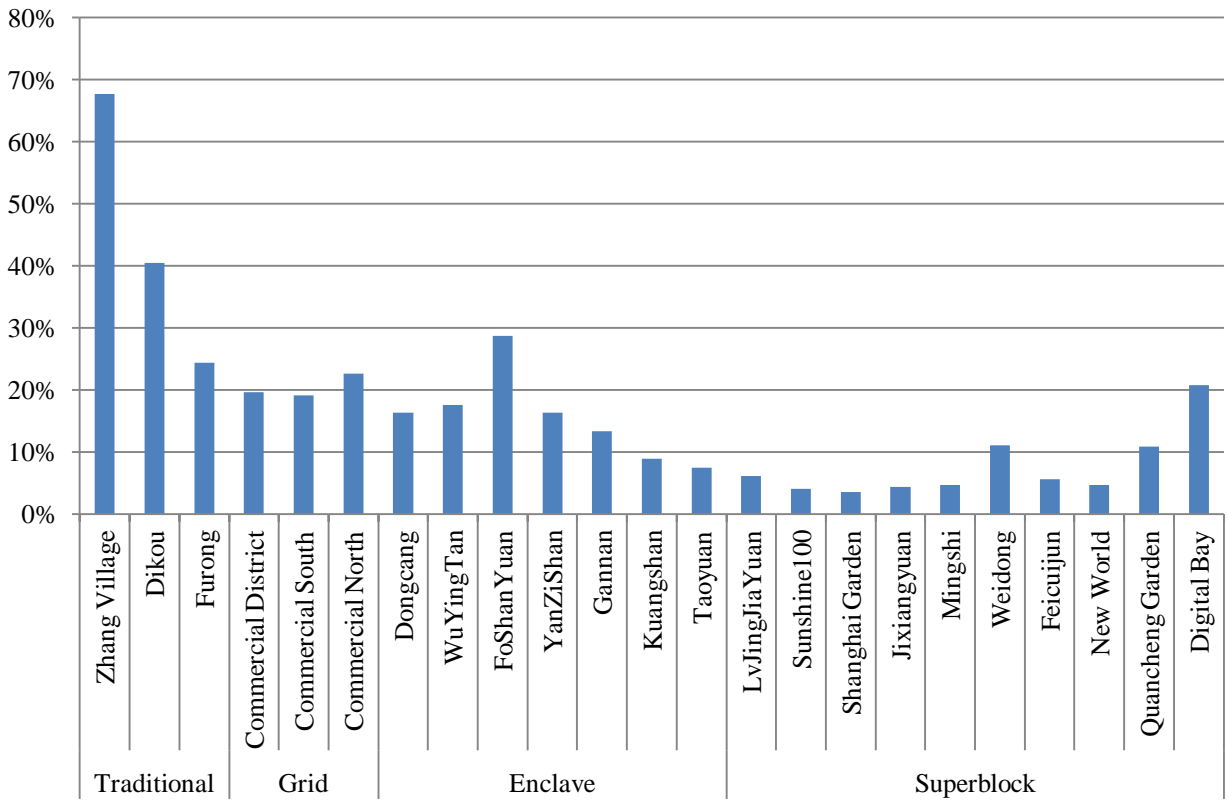
Neighborhood	Average Household Size
<b>Traditional</b>	2.80
<b>Grid</b>	2.86
<b>Enclave</b>	3.05
<b>Superblock</b>	3.17

*Source: Author*

The survey data reveal the connections between household size and household structure. The traditional typology has the smallest household size on average (2.80 people/household) because the residents in these neighborhoods include a large number of retired seniors and migrant workers whose other family members live elsewhere. The household size of the superblock neighborhoods is the largest (3.17 people/household) as these more spacious dwelling units tend to house multi-generation families more often.

Home ownership rates also vary greatly across different neighborhood typologies (see Figure 5 - 4). Generally, older neighborhoods tend to have a stronger presence of rental units. The three traditional neighborhoods have an average share of 52.76% rental units among all surveyed households, the highest among all typologies, corresponding to the strong presence of migrants. On the contrary, the newest superblocks neighborhoods, whose residents are mostly comparatively affluent home owners, have the lowest rental unit share of 6.40%.

**Figure 5 - 4 Percentages of Rental Units in Surveyed Neighborhoods**



Neighborhood	Percentage of Rental Units
<b>Traditional</b>	52.76%
<b>Grid</b>	20.29%
<b>Enclave</b>	16.79%
<b>Superblock</b>	6.40%

*Source: Author*

In summary, notable socio-demographic variation exists among the residential neighborhoods of different typologies. The traditional neighborhoods surveyed in the study, with a strong presence of retired people and migrant workers, have the lowest household income, the smallest household size, and the highest percentage of rental units. In contrast, the ten superblock neighborhoods, where the residents are mostly affluent home owners residing in comparatively spacious units, have the highest household income, the largest household size, and the lowest

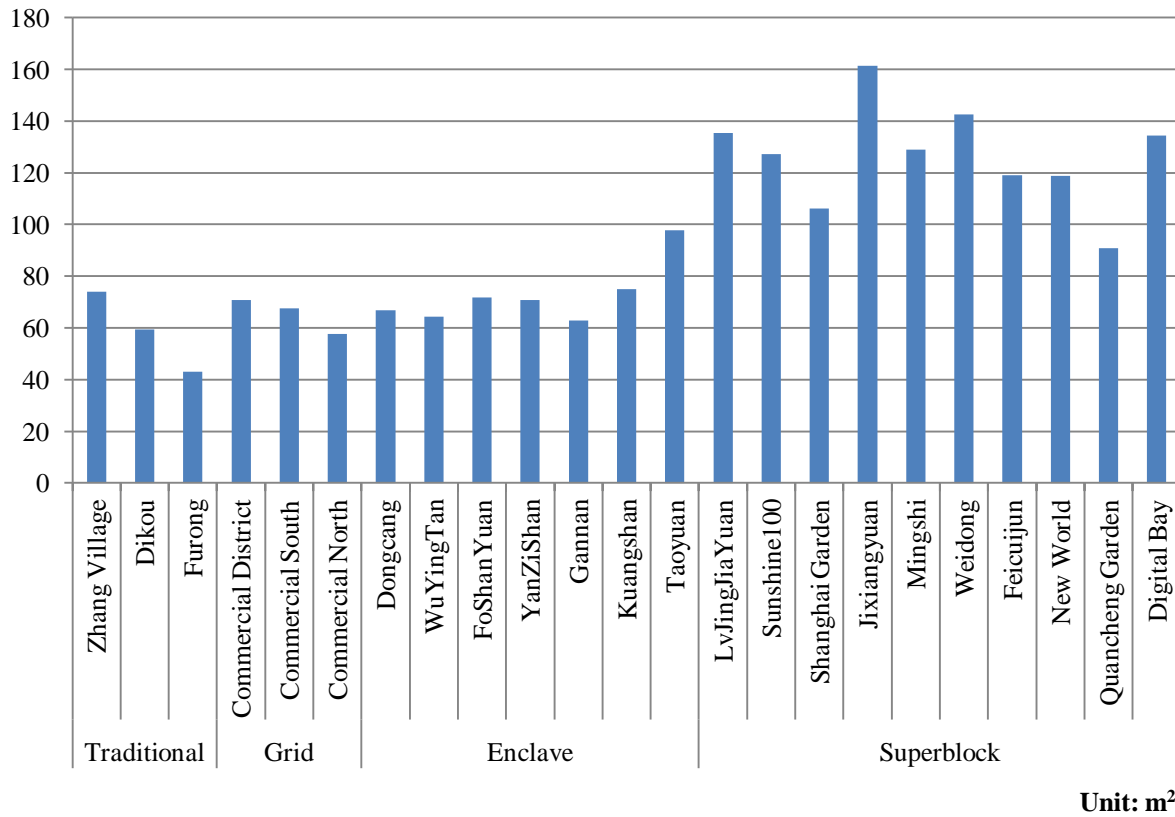
percentage of rental units. Once more, the grid and enclave neighborhoods appear in the middle, with no significant differences in socio-demographic parameters between these two typologies.

### **5.2.2 Dwelling Physical Attributes**

As introduced in Chapter 2, the four neighborhood typologies have been built in different stages of Jinan's urban development, ranging from pre-1910s to post-2000s. Consequently, the physical attributes of the dwellings in these 23 urban neighborhoods vary greatly from one another.

Unit area is one of the most obvious indicators of individual dwelling unit physical characteristics that the survey measured (see Figure 5 - 5). The first three neighborhood typologies (traditional, grid, and enclave) have similar average dwelling size, at around 65 m<sup>2</sup> per unit. However, the superblock neighborhoods have more spacious units, almost twice as big as those in the other three groups.

**Figure 5 - 5 Average Dwelling Unit Areas of Surveyed Neighborhoods**



Neighborhood	Average Dwelling Unit Area
<b>Traditional</b>	64.17
<b>Grid</b>	66.87
<b>Enclave</b>	71.17
<b>Superblock</b>	122.74

*Source: Author*

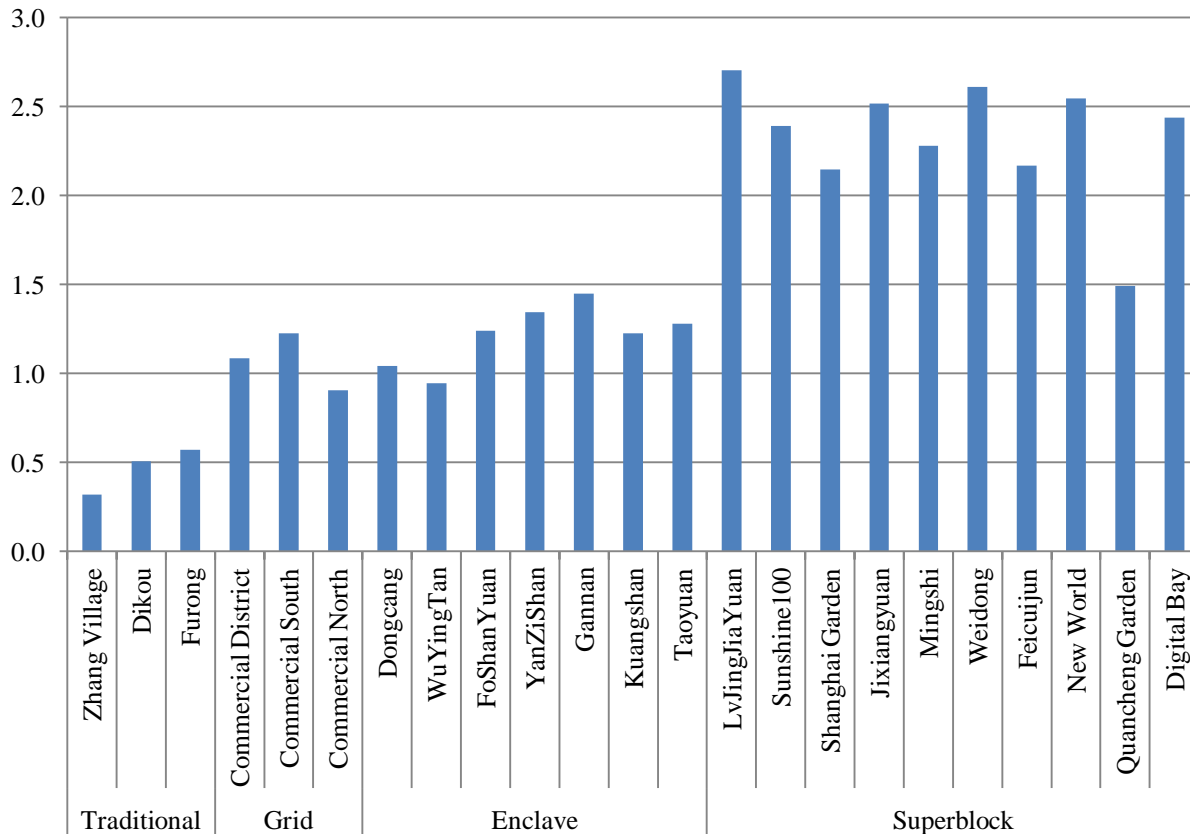
Such differences can be explained, in large part, by the construction period of these neighborhoods. The older neighborhoods, built before the 1980s when the overall living standards in China were lower, tend to have smaller units. On the contrary, the newer superblock units are significantly bigger as the private real estate developers have been trying to cater to their customers' growing expectations for home improvements.

### 5.2.3 Appliance Ownership

As mentioned previously, among the various household appliances, only air conditioners and solar water heaters were included in both years of the survey available for this research.

The ownership of air conditioners dramatically differs from one typology to another (see Figure 5 - 6). Less than half of the traditional neighborhood units are equipped with air conditioners, while the typical superblock unit has more than two air conditioners. The variation of air conditioner ownership is consistent with the differences in socio-demographic status of the households and the physical attributes of the neighborhoods. The traditional neighborhoods have fewer air conditioners and the residents are older, less affluent, and live in smaller units. The superblock households – with higher incomes, larger household sizes, and living in larger units – tend to own more air conditioners. The residents living in the grid and enclave neighborhoods own slightly more than one air conditioner per household on average.

**Figure 5 - 6 Household Air Conditioner Ownership of Surveyed Neighborhoods**



Neighborhood	Number of Air Conditioners Owned per Household
<b>Traditional</b>	0.41
<b>Grid</b>	1.08
<b>Enclave</b>	1.20
<b>Superblock</b>	2.29

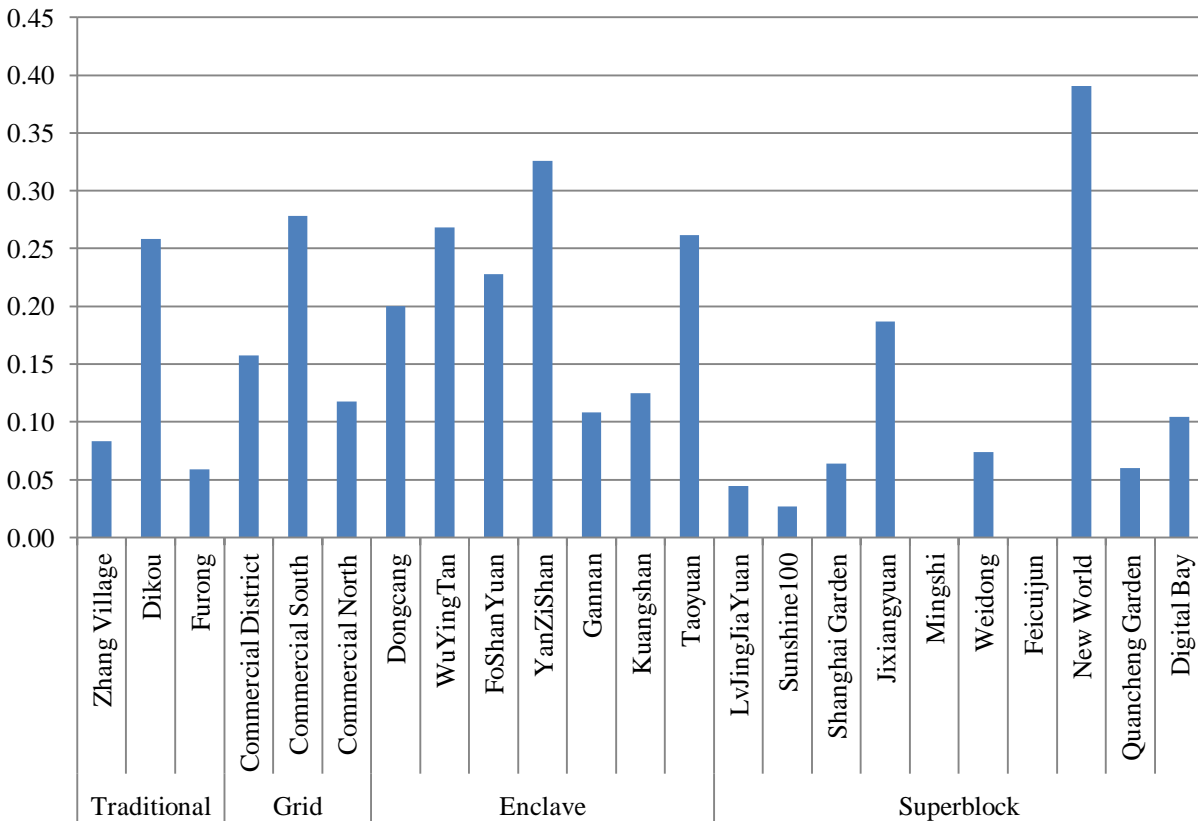
*Source: Author*

The pattern of solar water heater ownership is more complicated. Since households usually do not install more than one unit of solar water heater in their dwellings, the average number of solar water heaters owned per household can also be seen as the percentage of households who own a solar water heater. It is important to note that, unlike any other household characteristics that I have summarized, solar water heater ownership does not strictly vary together with



neighborhood typology (see Figure 5 - 7). Instead, solar hot water heater ownership varies more *within* each typology rather than across them. For example, within the enclave typology, almost one-third of the households have installed solar water heaters in the neighborhood with the highest coverage (Yanzishan) while in the neighborhood with the lowest coverage (Gannan) only 11% of households owns them.

**Figure 5 - 7 Household Solar Water Heater Ownership of Surveyed Neighborhoods**



Neighborhood	Number of Solar Water Heaters Owned per Household
<b>Traditional</b>	0.11
<b>Grid</b>	0.18
<b>Enclave</b>	0.23
<b>Superblock</b>	0.07

*Source: Author*

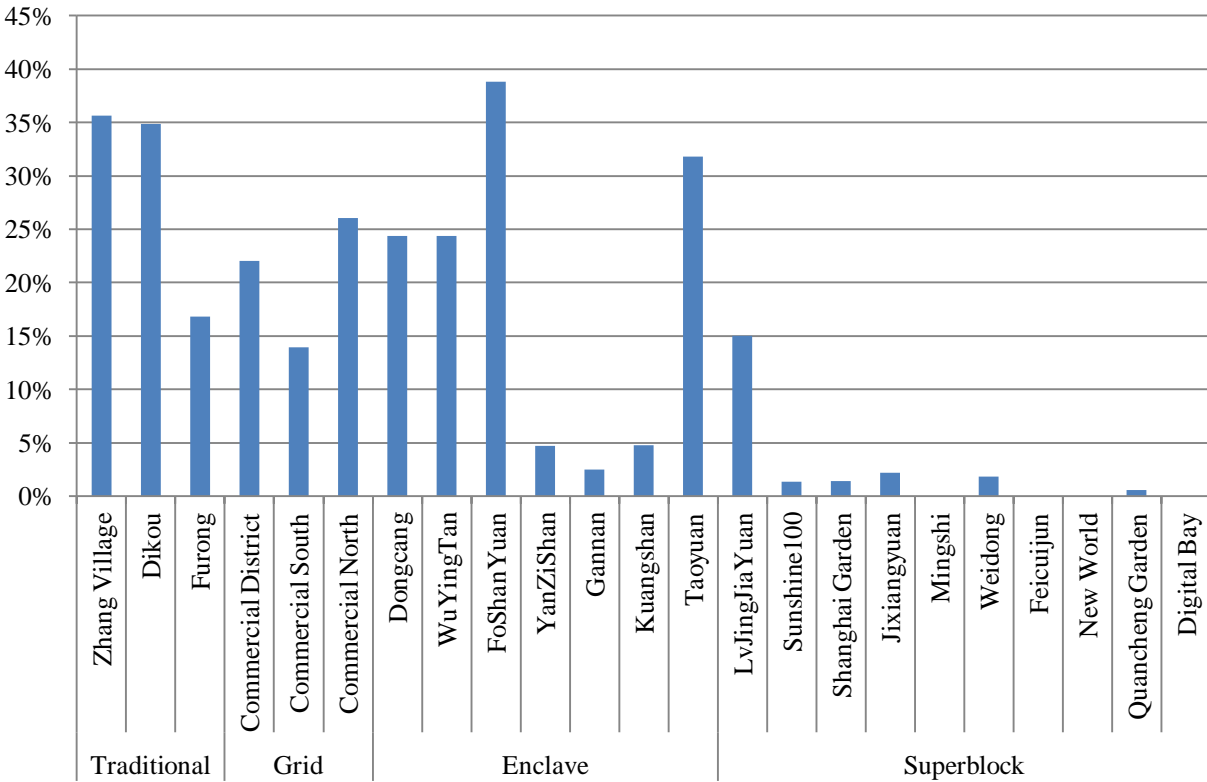
Overall, the superblock neighborhoods have the lowest number of solar water heaters per household, despite the fact that the New World superblock is the neighborhood that has the highest coverage of solar water heaters among all of the 23 neighborhoods. In two superblock neighborhoods, Mingshi and Feicuijun, no households surveyed had solar water heaters, possibly because the physical design and structure of the building roofs make installation impossible or very hard and/or the property managers in the neighborhoods have prohibited installation due to aesthetic or safety concerns.

#### **5.2.4 Usage Control**

The survey also inquired about how households heat their dwellings. Centralized heating is the most common heating method for homes in China; however, due to building age, structural limits and other reasons, a number of households choose to use alternative heating methods, including electric heating.

In general, the households living in traditional neighborhoods are the most likely to use electric heating, likely because a large number of old dwellings in the traditional neighborhoods do not have centralized heating systems. In both the grid and enclave neighborhoods, around one-fifth of the total households use electric heating. The superblock households are very unlikely to use electric heating as all residential buildings have already been equipped with centralized heating systems: Only a small percentage of the superblock households choose to use electric heating, likely as a supplementary heating method for their dwellings (see Figure 5 - 8).

**Figure 5 - 8 Percentages of Households with Electric Heating in Surveyed Neighborhoods**



Neighborhood	Percentage of Households with Electric Heating
<b>Traditional</b>	31.10%
<b>Grid</b>	21.11%
<b>Enclave</b>	19.24%
<b>Superblock</b>	3.23%

*Source: Author*

To conclude, household characteristics vary greatly across the different neighborhood typologies. Generally, the traditional neighborhoods are associated with the lowest household income, the smallest household size, the highest percentage of rental units, the smallest dwelling size, the lowest percentage of air conditioner ownership, and the highest coverage of electric heating. On the contrary, the superblock neighborhoods tend to have exactly the opposite household characteristics. The grid and enclave neighborhoods fall somewhere in between.

The only exception to these general patterns is the ownership of solar water heaters. The grid and enclave neighborhoods have the highest coverage of solar water heaters, followed by the traditional typology. The superblock neighborhoods have a very low presence of solar water heaters presumably due to the constraints of building design and structure and property management restrictions.

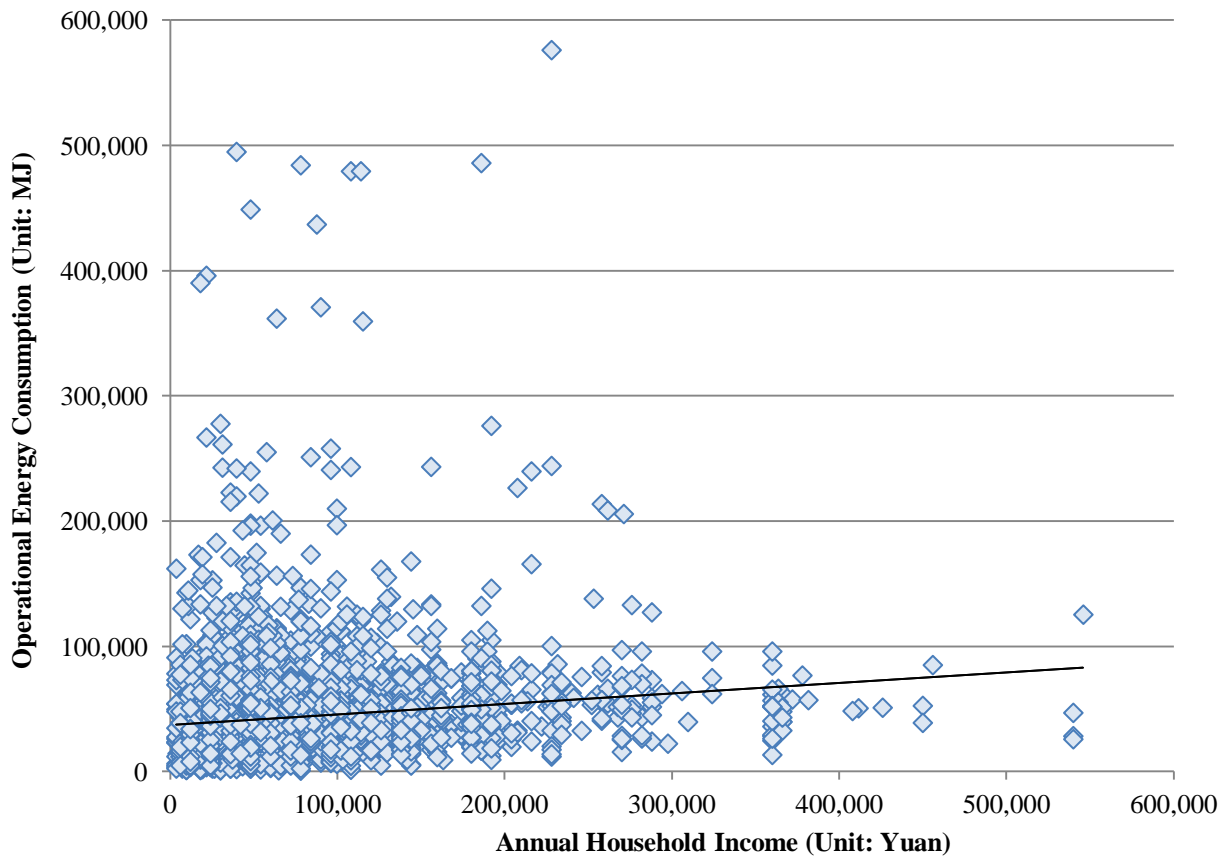
### **5.3 Household Characteristics and Operational Energy Consumption**

Two determining factors may help explain the differences in household characteristics across the four neighborhood typologies. First, the residents living in the four neighborhood typologies have very different economic and social backgrounds. The traditional neighborhood households are often composed of large numbers of retired people and migrant workers with limited financial resources. In contrast, the superblock households are much younger and more affluent. Second, the four typologies have very different size individual dwellings. The superblock neighborhoods, designed and constructed by private real estate developers after China's housing reform, have much larger unit areas than any other typology.

Such disparities in household characteristics can further manifest in differences in lifestyles and energy consumption behaviors. In this section, I descriptively illustrate the relationships between selected household characteristics and corresponding operational energy consumption.

Household income has a positive correlation with operational energy consumption (including electricity, gas, coal, and centralized heating altogether). As Figure 5 - 9 suggests, household operational energy consumption generally rises as household income increases.

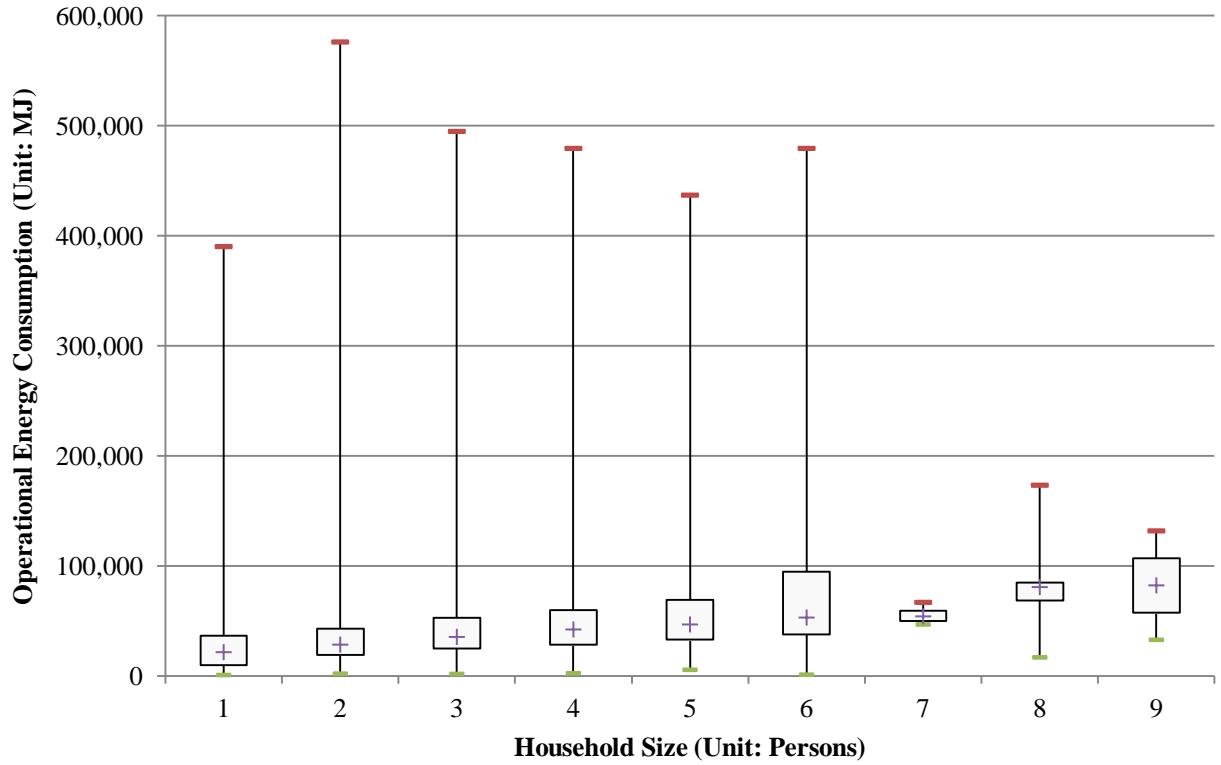
**Figure 5 - 9 Relationship between Annual Household Income and Operational Energy Consumption**



*Source: Author*

Household size also has an apparent positive correlation with operational energy consumption, as seen in the diagram in Figure 5 - 10.

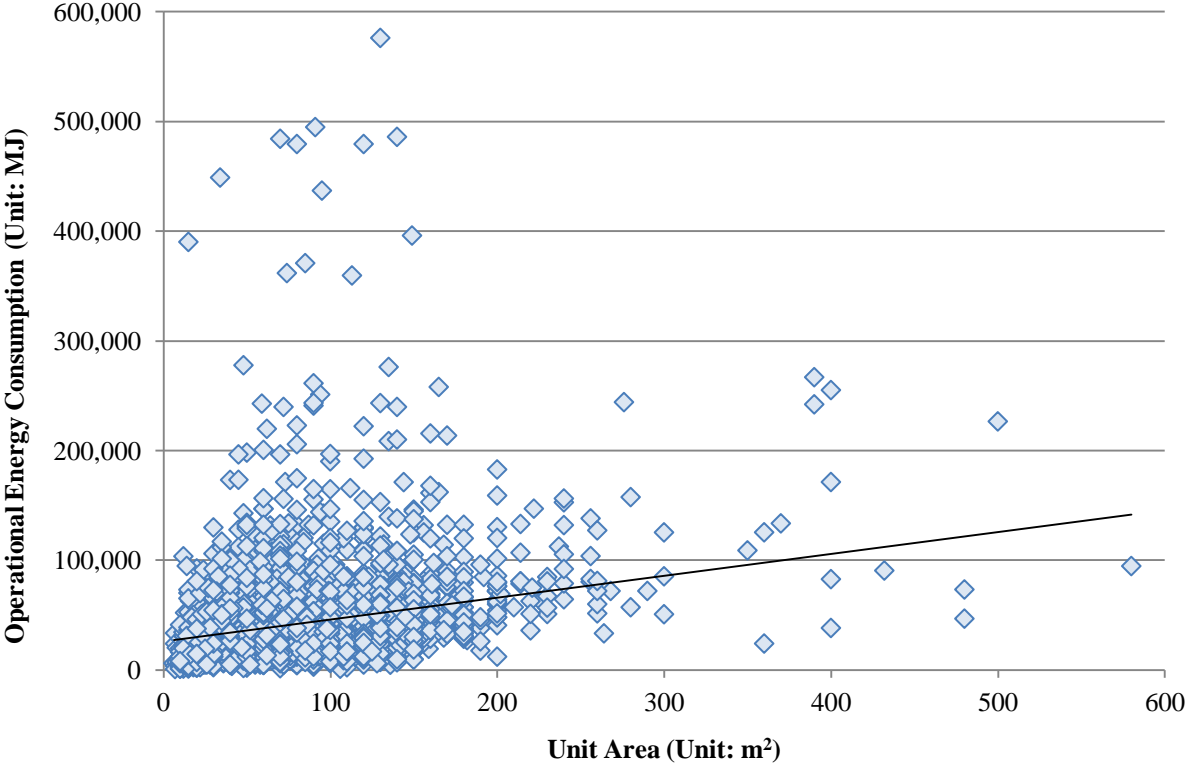
**Figure 5 - 10 Relationship between Household Size and Operational Energy Consumption**



*Source: Author*

As Figure 5 - 11 shows, larger dwelling units are generally associated with higher household operational energy consumption.

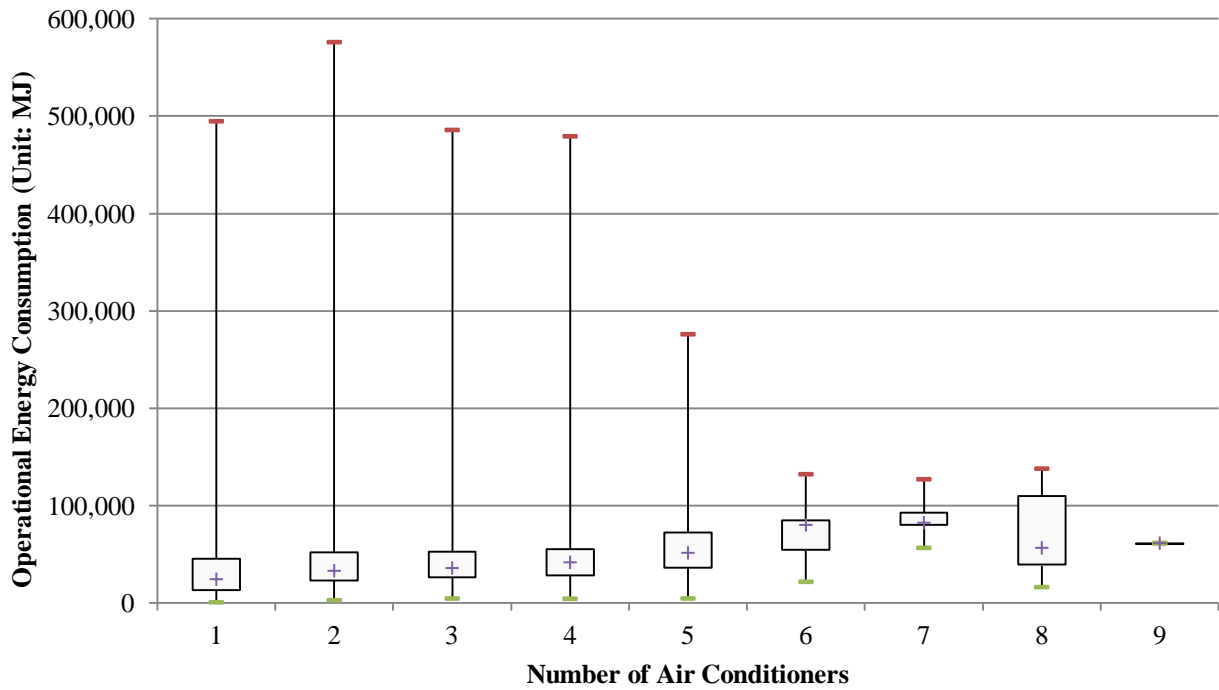
**Figure 5 - 11 Relationship between Dwelling Unit Area and Operational Energy Consumption**



*Source: Author*

Home appliance ownership may also be correlated with operational energy consumption as, for example, evidenced by the positive association between energy use and the number of air conditioners owned by households (see Figure 5 - 12).

**Figure 5 - 12 Relationship between Air Conditioner Ownership and Operational Energy Consumption**



*Source: Author*

The basic descriptive analyses reveal that certain household characteristics are correlated with operational energy consumption. In the following Chapter, I will turn to investigate the relationships between neighborhood characteristics and operational energy consumption.



## Chapter 6: Neighborhood Characteristics and Operational Energy Consumption

Following the analysis of the relationships between household characteristics and operational energy consumption, in this chapter I focus on the role of neighborhood characteristics. In the first section, I present an overview of selected urban form attributes of the Jinan neighborhoods. I then detail four aspects of neighborhood characteristics—i.e. density, mixed use, solar gain, and wind flow—providing descriptive comparisons of urban forms across the 23 surveyed neighborhoods. At the end of the chapter, I briefly explore the connections between these neighborhood characteristics and operational energy consumption.

### 6.1 Neighborhood Geographic Information System Data

The neighborhood characteristics analyzed in this study have been retrieved from geographic information system (GIS) data prepared by Beijing Normal University. Based on the GIS data, the parameters of neighborhood solar and wind performances have been analyzed and processed by Reza Amin Darbari and Shani Sharif at Massachusetts Institute of Technology.

The GIS data of the 23 selected Jinan neighborhoods cover a wide range of typical urban form attributes. A list of selected neighborhood characteristics, averaged at the typology level, is displayed in Table 6 - 1. As expected, the neighborhood characteristics vary greatly from one typology to another, revealing the relatively distinct urban form of each individual typology. For example, the traditional neighborhoods have the highest average building coverage ratio *and* the lowest floor area ratio, indicating that these neighborhoods mostly consist of low-rises with narrow alleys running through without the presence of much public space. On the contrary, the lowest building coverage ratio and the highest floor area ratio are both associated with the superblock neighborhoods, evidence of the fact that high-rises and large common open spaces are often seen in these gated communities.

**Table 6 - 1 Selected Neighborhood Characteristics of Four Typologies**

	<b>Tradi- tional</b>	<b>Grid</b>	<b>Enclave</b>	<b>Super- block</b>
<b>Floor Area Ratio</b>	1.01	2.07	1.71	2.10
<b>Building Coverage Ratio</b>	49.56%	36.47%	34.91%	20.25%
<b>Average Building Height (m)</b>	2.04	5.81	4.92	11.28
<b>Building Function Mix</b>	0.22	0.39	0.26	0.08
<b>Percentage of Residential Building</b>	83.24%	43.97%	80.42%	94.34%
<b>Entry Interval Distance (m)</b>	343.26	201.05	168.40	569.09
<b>Green Coverage Ratio</b>	1.23%	4.99%	11.31%	15.28%
<b>Percentage of Roads with Trees</b>	14.49%	42.14%	44.21%	49.14%
<b>Percentage of Residential Building with Street-Level Shops</b>	8.42%	6.06%	13.53%	2.96%
<b>Percentage of Roads with Walking Facilities</b>	72.04%	68.88%	42.32%	44.11%
<b>Road Density (km/km<sup>2</sup>)</b>	25.21	19.26	28.42	30.19
<b>Average Motorway Width (m)</b>	8.58	7.27	6.89	12.02
<b>Surface To Volume Ratio</b>	0.818	0.539	0.423	0.292
<b>Summer Shadow Ratio (Roofs)</b> (Percentage of roof area in shadow on the summer solstice)	0.000	0.013	0.009	0.009
<b>Summer Shadow Ratio (Fa çades)</b> (Percentage of fa çades area in shadow on the summer solstice)	0.176	0.071	0.067	0.150
<b>Winter Shadow Ratio (Roofs)</b> (Percentage of roof area in shadow on the winter solstice)	0.029	0.102	0.067	0.075
<b>Winter Shadow Ratio (Fa çades)</b> (Percentage of fa çades area in shadow on the winter solstice)	0.430	0.261	0.260	0.305
<b>Summer Solar Gain</b> (Percentage of surface area not in shadow times sine of the angle between fa çades and solar beam on the summer solstice)	0.323	0.322	0.339	0.242
<b>Winter Solar Gain</b> (Percentage of surface area not in shadow times sine of the angle between fa çades and solar beam on the winter solstice)	0.247	0.277	0.288	0.255
<b>Porosity</b> (Fraction of void space volume over neighborhood total volume)	0.534	0.648	0.652	0.766
<b>Height Irregularity</b> (Average building height deviation from the mean height)	1.664	10.678	4.020	14.002
<b>Buildings/Wind Orientation Index (Summer)</b> (Percentage of fa çades with maximum exposure orientation to prevailing summer winds)	0.715	0.719	0.723	0.728
<b>Buildings/Wind Orientation Index (Winter)</b> (Percentage of fa çades with maximum exposure orientation to prevailing winter winds)	0.654	0.697	0.735	0.723

*Source: Author,*

*based on calculations by Darbari and Sharif (2011) and data provided by Beijing Normal University*

Many of these neighborhood characteristics have mutual influences on each other. For instance, neighborhoods with a higher green coverage ratio are likely to have lower building coverage ratio, and summer shadow ratio and winter shadow ratio are highly correlated. Such mutual correlations can often result in the problem of multicollinearity if all of them are included in a regression analysis. Therefore, I select four variables that have minimal correlations and represent four distinctive aspects of neighborhood characteristics:

- **Density:** floor area ratio<sup>4</sup>;
- **Mixed use:** building function mix;
- **Solar gain:** summer solar gain index;
- **Wind flow:** porosity.

## 6.2 Overview of Neighborhood Characteristics

Similar to the household characteristics discussed in the previous chapter, different neighborhoods present strong variation in urban forms.

### 6.2.1 Density

Figure 6 - 1 showcases the vast variation of floor area ratios among all surveyed neighborhoods. Generally, the traditional typology has the lowest floor area ratio (1.01) as most dwellings in the neighborhoods are one or two-storey low-rises. The highest average floor area ratios belong to the grid and superblock neighborhoods (2.07 and 2.10 respectively) because new high-rise developments typically only exist in these two typologies.

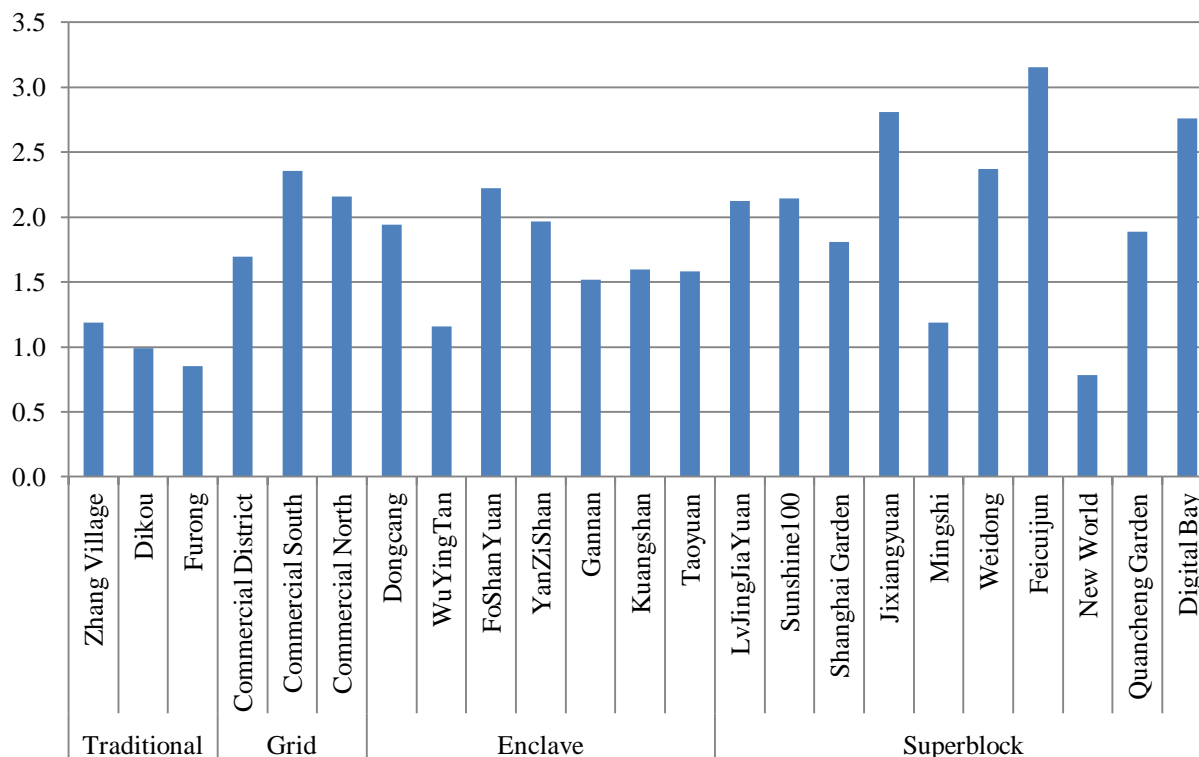
However, note that the neighborhoods, especially the superblocks, also have strong differences in floor area ratio within their respective typology groups. New World, a superblock neighborhood, has the lowest floor area ratio among the 23 neighborhoods. The floor area ratio of Mingshi, another superblock neighborhood, is also one of the lowest in the whole group. Though the average building heights of New World and Mingshi are taller than most of the other neighborhoods, they are distinctively characterized by the presence of large open spaces, large

---

<sup>4</sup> Floor area ratio is the ratio of total building floor area to the neighborhood parcel area, and is one commonly used indicator to portray density. However, it is not a direct measurement of density, and using it without referencing other density measurements, such as dwelling units per acre or population per acre, is often insufficient to accurately depict density and physical form of neighborhoods (Density Atlas, 2012). In this research, I still choose to use floor area ratio as a proxy of density because it is widely used as a metric in design and planning regulations in China.

distances between buildings, and wide internal roadways. These design elements, pursued by the developers in order to attract the most affluent “high-end” property buyers, significantly reduce the floor area ratio of these superblock neighborhoods.

**Figure 6 - 1 Floor Area Ratios of Surveyed Neighborhoods**



Neighborhood	Floor Area Ratio
<b>Traditional</b>	1.01
<b>Grid</b>	2.07
<b>Enclave</b>	1.71
<b>Superblock</b>	2.10

*Source: Author*

### 6.2.2 Mixed Use

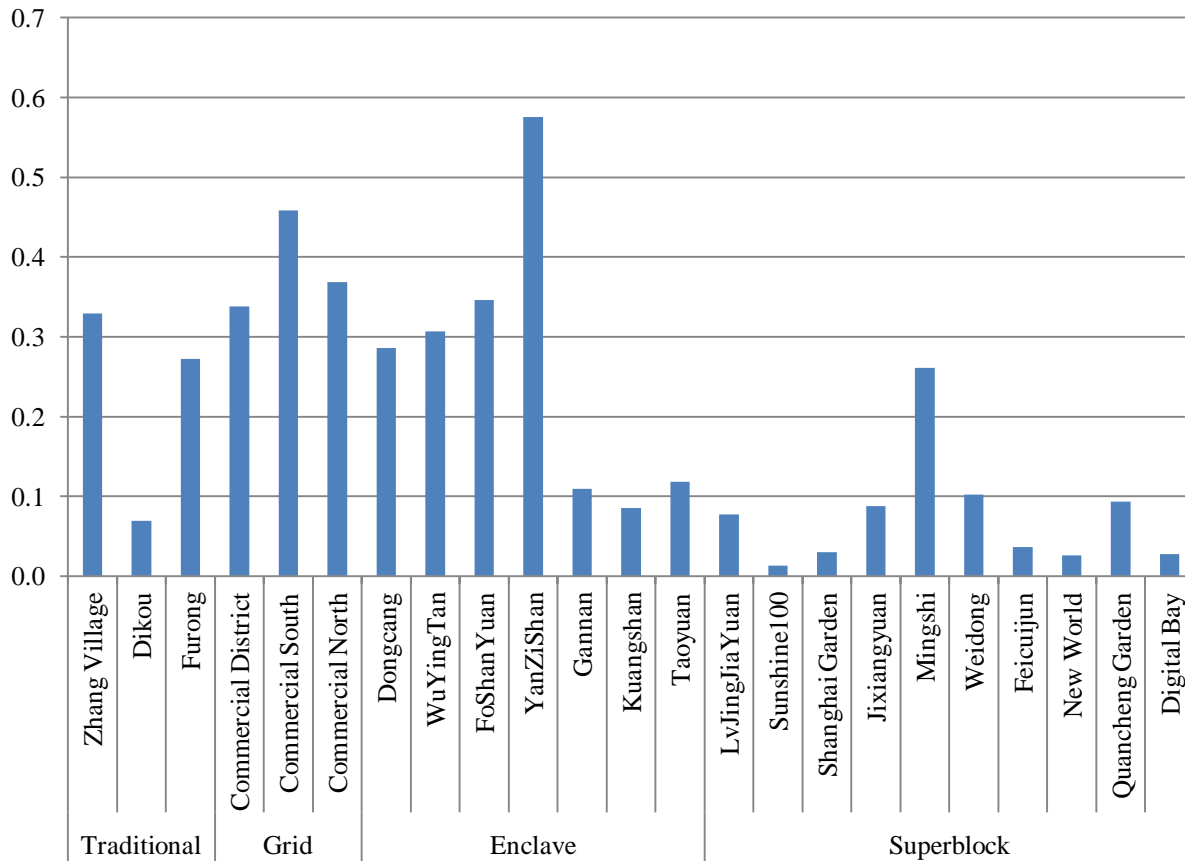
The four neighborhood typologies have distinctive patterns of mixed use as evidenced by vast variation of building function mix indices. Though residential is the primary use of the 23

neighborhoods, all of them have certain portions of neighborhood spaces for other functions. In this research, the building function mix index of a neighborhood indicates the deviation of percentages of buildings with residential, commercial, industrial, and other functions within its boundary. The higher the index is, the more mixed-use the neighborhood is.

Intuitively, the superblock neighborhoods have the lowest average building function mix because most of these developments are gated communities, with very limited penetration of other activities into their spaces. The grid neighborhoods, which have undergone the most urban redevelopment, have the most diverse mixed use (see Figure 6 - 2).

Similar to floor area ratio, there are also exceptions in the above general pattern of building function mix. The two neighborhoods with the highest building function mix, Yanzishan and Mingshi, are not grid neighborhoods. This may well be due to the fact that both of these neighborhoods are located in the southeastern suburbs of Jinan, where transportation to other parts of the city is rather inconvenient. Therefore, most of the commercial/retail and other facilities all tend to be agglomerated inside the neighborhood boundary, increasing the building function mix of these two neighborhoods.

**Figure 6 - 2 Building Function Mix Indices of Surveyed Neighborhoods**



Neighborhood	Building Function Mix
<b>Traditional</b>	0.22
<b>Grid</b>	0.39
<b>Enclave</b>	0.26
<b>Superblock</b>	0.08

*Source: Author*

### 6.2.3 Solar Gain

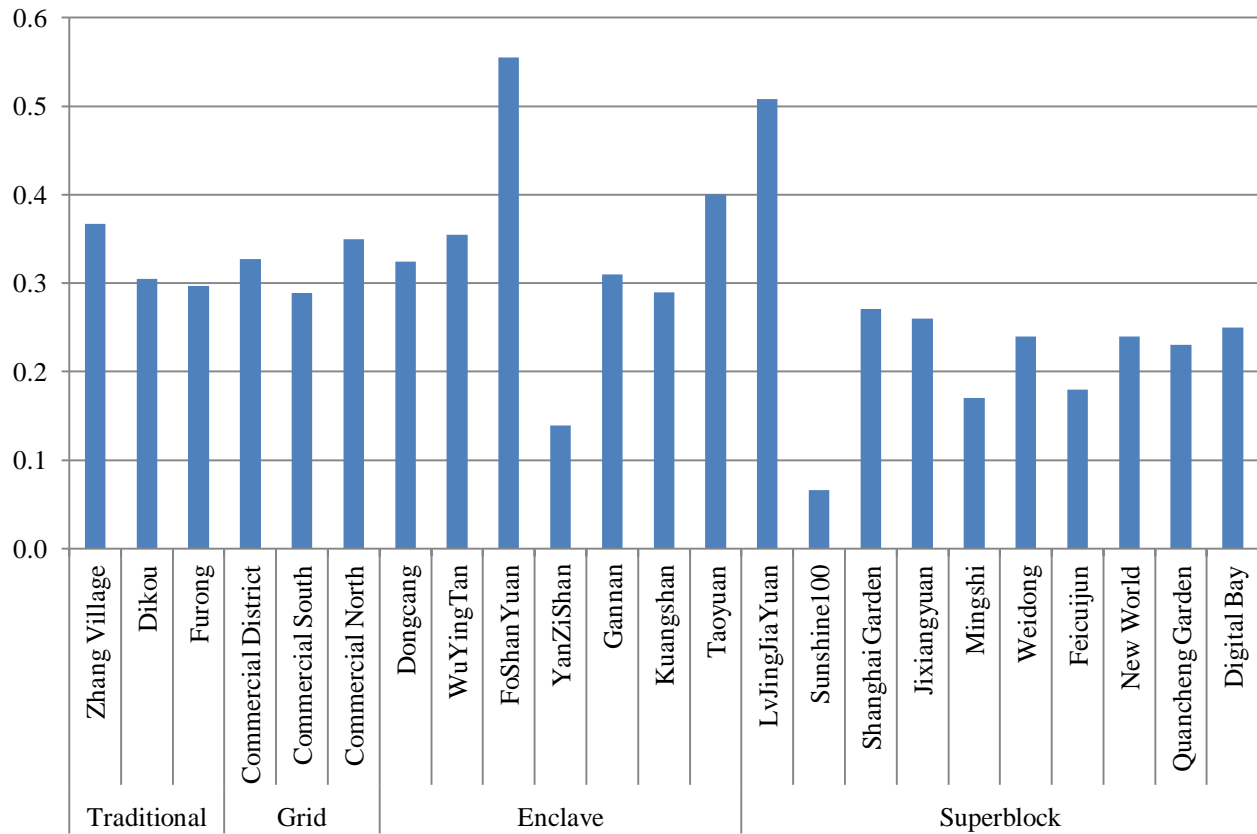
Solar gain can have a profound impact on energy consumption as some occupants' energy usage behavior (lighting, heating, and cooling) relate to the amount of solar radiation. In this study, the solar gain index is defined based on both the shading condition and the façades orientation of all buildings in the neighborhood.<sup>5</sup>

Figure 6 - 3 indicates that the superblock neighborhoods have the lowest average summer solar gain index while the other three typologies have somewhat comparable values. The reason behind this result can be traced to building heights. The superblock neighborhoods tend to have the tallest buildings and the largest building height variation. Taller buildings are more likely to cast shadows on the roofs and façades of shorter ones, which possibly explains why the summer solar gain indices of superblock neighborhoods appear lower.

---

<sup>5</sup> The summer solar gain index is calculated as the product of the percentage of building surface not in shadow and the sine of the angle between façades and solar beam (Darbari and Sharif, 2011). The summer and winter solar gain indices are highly correlated, and in this research I choose to include summer solar gain index as a neighborhood characteristic. The summer solar gain indices used in this study are the average of three measurement times over the summer (10:30am, noon, and 1:30pm on the summer solstice).

**Figure 6 - 3 Summer Solar Gain Indices of Surveyed Neighborhoods**



Neighborhood	Summer Solar Gain Index
<b>Traditional</b>	0.323
<b>Grid</b>	0.322
<b>Enclave</b>	0.339
<b>Superblock</b>	0.242

*Source: Author*

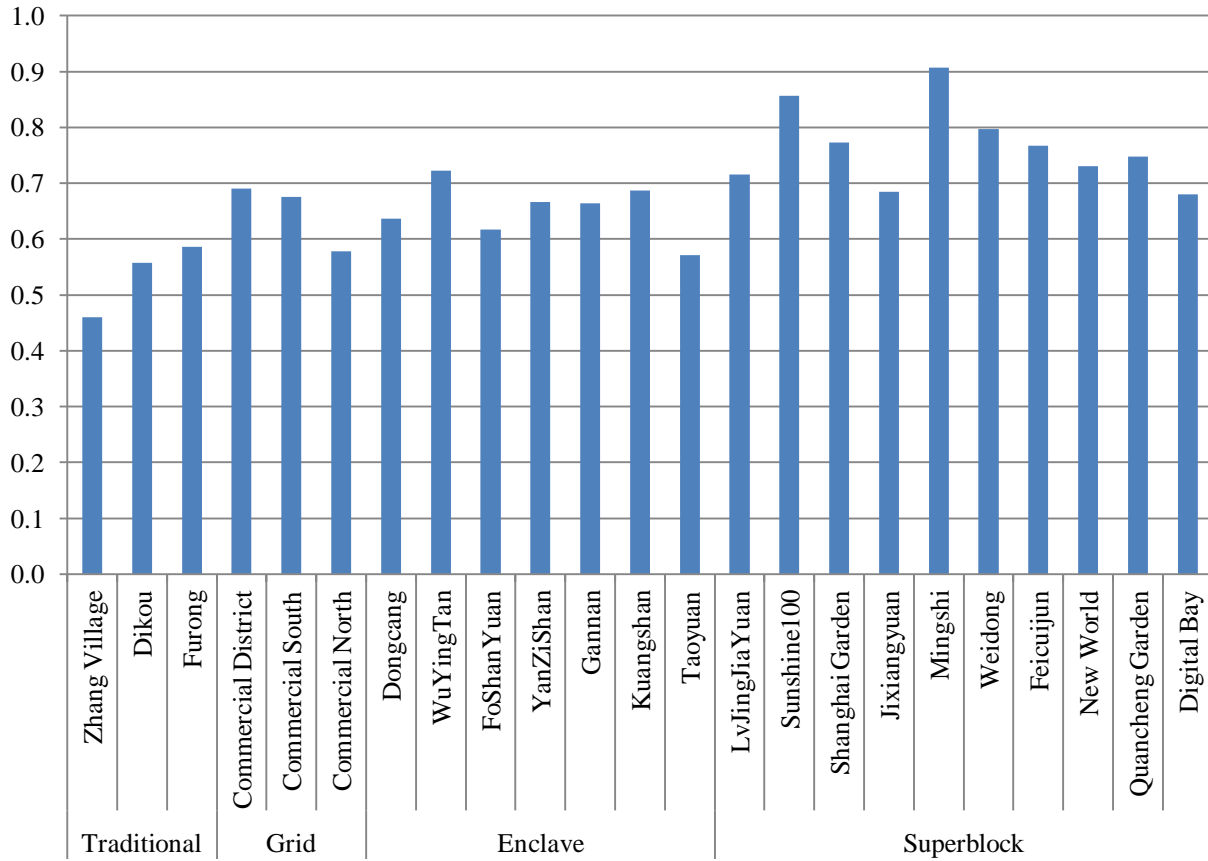


#### 6.2.4 Wind Flow

Wind flow within a neighborhood may also have a strong impact on operational energy consumption as it also affects the heating and cooling performance of the buildings. In this research, wind flow performance is represented by porosity, the fraction of the volume of void spaces over the total volume of the neighborhood (Darbari and Sharif, 2011).

The four neighborhood typologies display distinctive patterns of porosity (see Figure 6 - 4). Traditional neighborhoods have the lowest average porosity indices while the superblocks have the highest. This is partly influenced by the fact that the traditional neighborhoods are mostly composed of low-rises with very little public space in between while the superblock typology is characterized by high-rises of sharp height irregularity with large flat open space. There are no obvious differences between the grid and enclave neighborhoods' porosity indices.

**Figure 6 - 4 Porosity Indices of Surveyed Neighborhoods**



Neighborhood	Porosity Index
<b>Traditional</b>	0.534
<b>Grid</b>	0.648
<b>Enclave</b>	0.652
<b>Superblock</b>	0.766

*Source: Author*

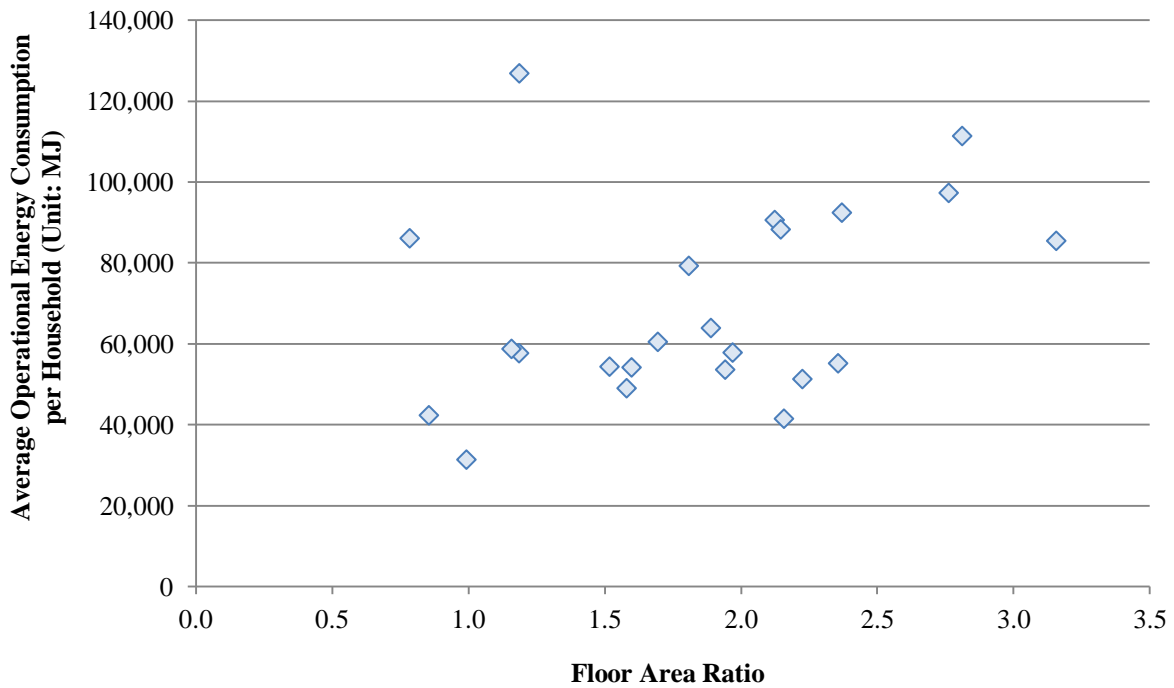
### 6.3 Neighborhood Characteristics and Operational Energy Consumption

In this section, I illustrate the relationships between the selected neighborhood characteristics and neighborhood average operational energy consumption per household. The descriptive analyses reveal some apparent relationships between neighborhood characteristics and operational energy consumption of households. Nonetheless, these relationships should be

viewed with great caution, since they do not consider the household characteristics which we know also influence demand for energy.

The floor area ratio has a positive correlation with operational energy consumption (see Figure 6 - 5), although this result is likely due to the fact that most neighborhoods having higher floor area ratios are superblock neighborhoods, which have larger and wealthier households in larger dwelling units (see Chapter 4).

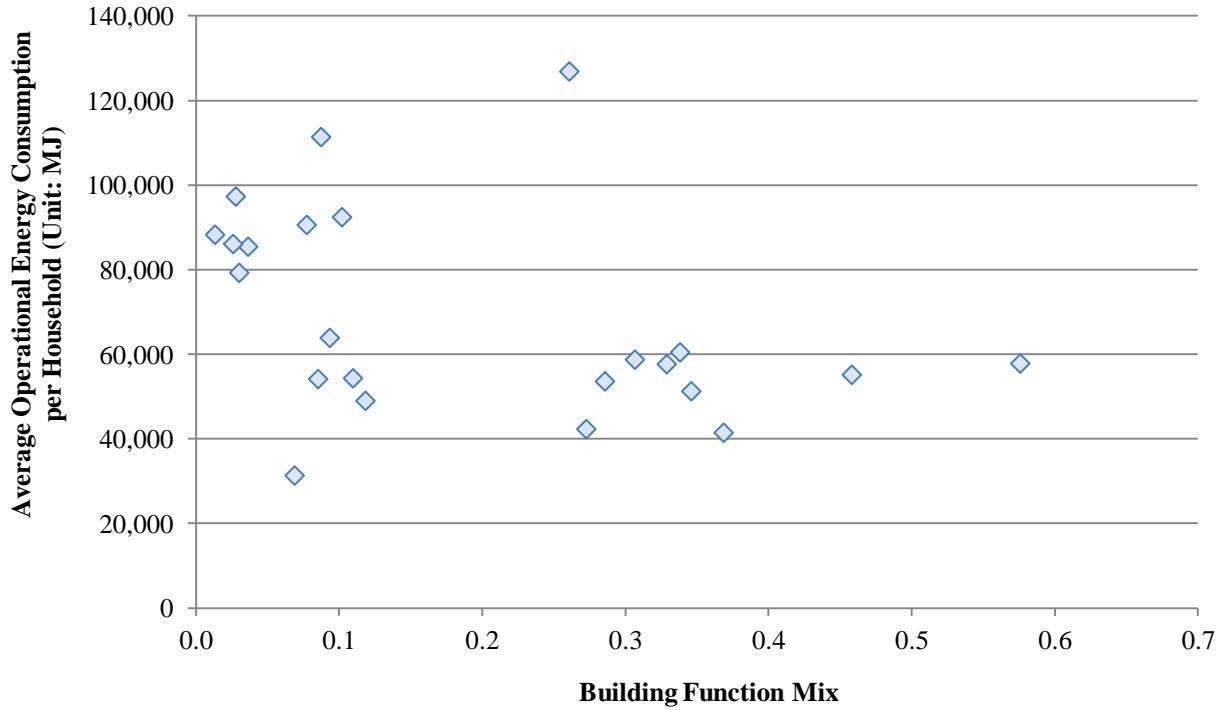
**Figure 6 - 5 Relationship between Floor Area Ratio and Operational Energy Consumption**



*Source: Author*

Neighborhood average building function mix has a negative correlation with average operational energy consumption (see Figure 6 - 6). This result may be due to the fact that the grid and enclave neighborhoods, which have more modest income households, tend to have higher mix of uses. Again, we cannot conclude more without controlling for household characteristics.

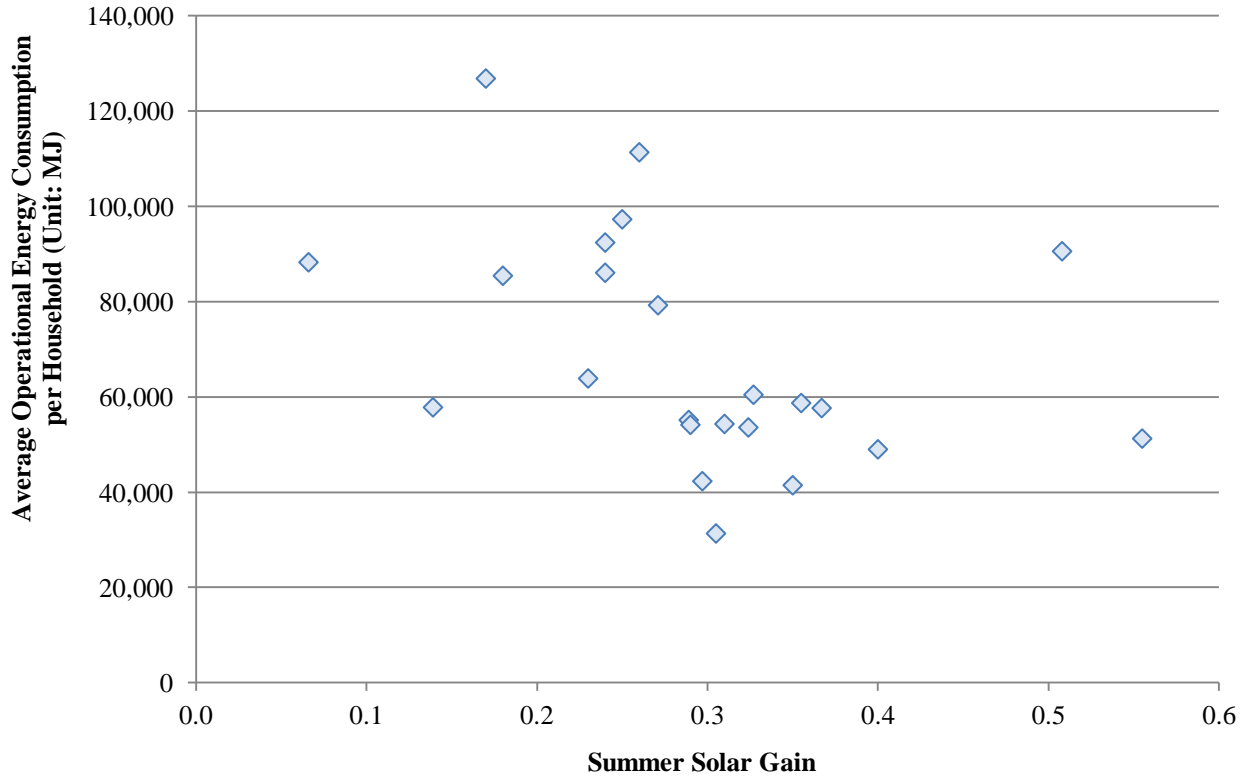
**Figure 6 - 6 Relationship between Building Function Mix and Operational Energy Consumption**



*Source: Author*

Figure 6 - 7 illustrates an apparent negative correlation between neighborhoods with higher summer solar gain indices and average household operational energy consumption. Again, this may be a result of the superblocks, which tend to have low summer solar gain indices and wealthier and larger households in large dwelling units.

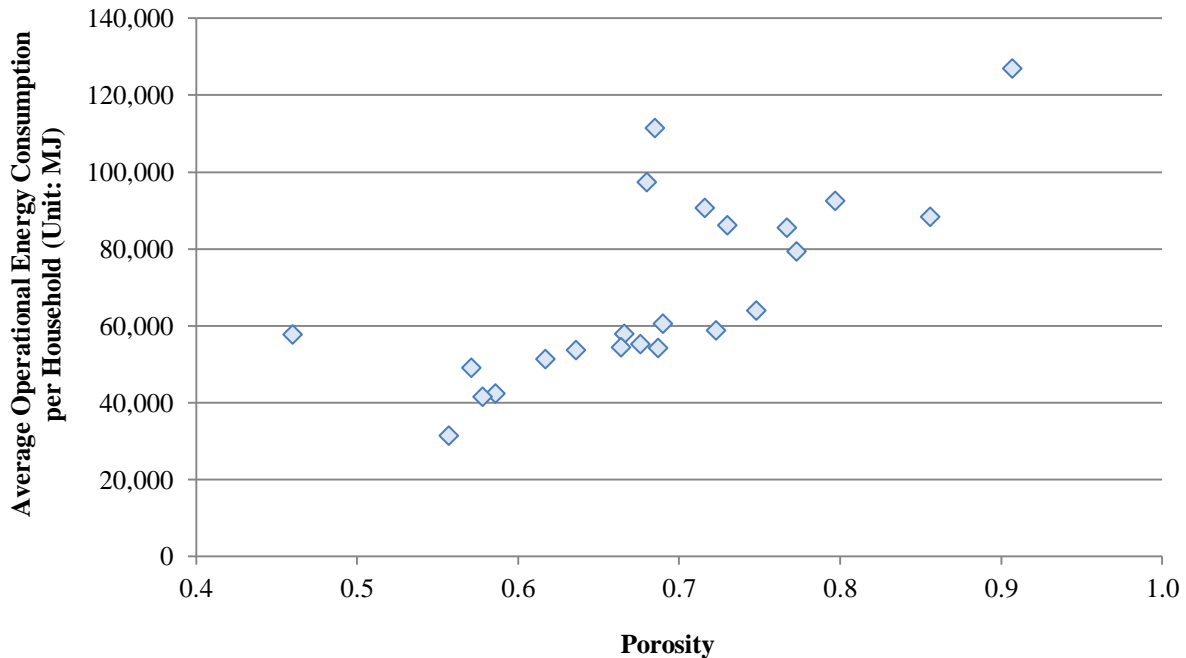
**Figure 6 - 7 Relationship between Summer Solar Gain Index and Operational Energy Consumption**



*Source: Author*

Finally, porosity seems to be positively correlated with energy consumption (see Figure 6 - 8). Again, it is possibly a result of the superblock neighborhoods, with slightly higher on average porosity, and their more energy consuming households.

**Figure 6 - 8 Relationship between Porosity and Operational Energy Consumption**



*Source: Author*

In this chapter, I have analyzed floor area ratio, building function mix, summer solar gain, and porosity indices as the representative neighborhood characteristics. I depict the correlations between urban form and operational energy consumption; however, on their own, these correlations tell us little about the relationship between urban form and household operational energy use, since they ignore the role of the household characteristics themselves.

In the next chapter, I will present the multilevel, multivariate regression model, which incorporates both the household and neighborhood variables which have been presented in this Chapter and the previous one. Such a model creatively combines analyses on individual and contextual information together and thus can provide a clearer picture of the true factors impacting household operational energy consumption.

## **Chapter 7: Multilevel Analysis: Household, Neighborhood, and Interaction Effects on Energy Consumption**

Following the descriptive analyses of the association of household energy consumption with household and neighborhood characteristics, I now turn to multilevel analysis to further investigate the statistical correlations among these factors.

As households are nested within neighborhoods, the multilevel analysis approach entails a regression model that organizes data at more than one level. In this chapter, I will first present a preliminary analysis of the household operational energy consumption within and between residential neighborhoods in Jinan. The results suggest that significant variation exists in energy usage across different neighborhoods, and show the need to apply multilevel analysis. Then, I introduce the framework and specification of the multilevel regression model, and demonstrate the regression results and analysis for the surveyed households and neighborhoods. Based on a multilevel regression model which takes the household characteristics as lower-level variables and the neighborhood characteristics as higher-level variables, I examine the household, neighborhood, and interaction effects on operational energy consumption.

### **7.1 Analysis of Variance within and between Neighborhoods**

Before proceeding to multilevel analysis, I first conduct an Analysis of Variance (ANOVA) to examine whether or not there is significant variation among household operational energy consumption within and between residential neighborhoods.

As explained in Chapter 3, I intend to use multilevel analysis to isolate the household effect and the structural and contextual neighborhood effects, but also cross-level interaction effects where urban form may influence operational energy consumption indirectly through impacts on household characteristics. The ANOVA results lay the foundation for the multilevel regression model presented in the following section.

If the ANOVA results suggest there is little variation in household energy consumption in different neighborhoods, then specifying neighborhood-level data and conducting a two-level regression analysis is not likely to provide additional information and to indicate the role of neighborhood characteristics in shaping operational energy consumption. However, if the

ANOVA reveals significant variation of energy consumption across the neighborhoods, the multilevel analysis will likely be helpful in examining the outcome of both the household- and neighborhood-level and the cross-level effects.

The ANOVA model includes two levels of analysis. The first level examines the variation of household energy consumption within each neighborhood, and the second level examines the variation between different neighborhoods. By combining the results from the two levels together, the model can show what portion of the total variation in operational energy consumption occurs at the household and neighborhood levels respectively.

### 7.1.1 First Level: Variance within Neighborhoods

The first level in the ANOVA model analyzes the within-group variance, i.e. the variance of operational energy consumption within each residential neighborhood. The equation is defined as:

$$\text{LN\_TMJ}_{ij} = \text{NBH}_j + r_{ij} \quad (7-1)$$

Where:

- $\text{LN\_TMJ}_{ij}$  is the natural log of the estimated total operational energy consumption of household  $i$  in neighborhood  $j$ ;
- $\text{NBH}_j$  is the intercept of neighborhood  $j$  from the second level equation (7-2) of the ANOVA model;
- $r_{ij}$  is the first-level error term, indicating the within-group residual;  $r_{ij} \sim N(0, \theta)$ .

### 7.1.2 Second Level: Variance between Neighborhoods

The second level in the ANOVA model analyzes between-group variance, i.e. the variance of operational energy consumption between different residential neighborhoods. The equation is defined as:



$$NBH_j = \overline{NBH} + u_j \quad (7-2)$$

Where:

- $NBH_j$  is the group mean, i.e. the average natural log of household operational energy consumption of neighborhood  $j$ ;
- $\overline{NBH}$  is the grand mean, i.e. the average natural log of household operational energy consumption of all neighborhoods;
- $u_j$  is the second-level error term, indicating between-group residual;  $u_j \sim N(0, \varphi)$ .

### 7.1.3 Results: Significant Variation at Both Levels

The full ANOVA model is presented below after combining Equations 7-1 and 7-2:

$$LN\_TMJ_{ij} = \overline{NBH} + u_j + r_{ij} \quad (7-3)$$

It shows that the model is composed of a grand mean,  $\overline{NBH}$ , a neighborhood-level error term (between-group residual),  $u_j$ , and a household-level error term (within-group residual),  $r_{ij}$ , with  $u_j \sim N(0, \varphi)$ ,  $r_{ij} \sim N(0, \theta)$ .

In this ANOVA model, the response variable  $LN\_TMJ$ , the natural log of household total estimated operational energy consumption, includes electricity, coal, and gas consumptions but excludes centralized heating usage. As previously explained in Chapter 4, heating in China is not metered, thus I am unable to acquire information on heating energy consumption directly. Instead, I use unit area to estimate the centralized heating energy consumption for the households. Since this part of operational energy consumption is directly derived from unit area, which will be later used as an independent variable in the regression analysis, I have to exclude centralized heating from the total energy consumption.

The ANOVA results are shown in Table 7 - 1.

**Table 7 - 1 Analysis of Variance Results of Household Operational Energy Consumption within and between Neighborhoods in Jinan**

Parameter	Estimated Coefficient	Standard Error	95% Confidence Interval	
LN_TMJ	10.446	0.0396	10.368	10.523
$\sqrt{\hat{\varphi}}$ (Standard Deviation of $u_j$ )	0.179	0.0299	0.129	0.248
$\sqrt{\hat{\theta}}$ (Standard Deviation of $r_{ij}$ )	0.713	0.0082	0.698	0.730

LR test vs. linear regression: **chibar2(01) = 159.01 Prob >= chibar2 = 0.0000**

**Number of Observations: 3838; Number of Groups: 23**

*Source: Author*

The results suggest that significant variation in household operational energy consumption exists both within and between neighborhoods (The estimated standard deviations of residuals at both levels are significantly different from zero, using the significance level  $\alpha=0.05$ ). It is, thus, legitimate to carry out a multilevel regression analysis to examine the effects within and between the two levels.

In addition, the intraclass correlation,  $\rho$ , can be calculated using the estimates of the variances of the between-group and within-group residuals:

$$\hat{\rho} = \frac{\hat{\varphi}}{\hat{\varphi} + \hat{\theta}} = \frac{(\sqrt{\hat{\varphi}})^2}{(\sqrt{\hat{\varphi}})^2 + (\sqrt{\hat{\theta}})^2} \quad (7-4)$$

As indicated by the equation, the greater the variation between different groups, the higher the value of the intraclass correlation is. The estimated intraclass correlation of all surveyed households in this research is:

$$\hat{\rho} = \frac{\hat{\varphi}}{\hat{\varphi} + \hat{\theta}} = \frac{(\sqrt{\hat{\varphi}})^2}{(\sqrt{\hat{\varphi}})^2 + (\sqrt{\hat{\theta}})^2} = \frac{0.179^2}{0.179^2 + 0.713^2} = 0.059$$

This means that, of the total variation in operational energy consumption among surveyed households, roughly 5.9% occurs between neighborhoods while 94.1% lies at individual level within neighborhoods.

The ANOVA results suggest that significant variation exists within and between neighborhoods. I now turn to multilevel regression analysis to investigate the contributing factors at both household and neighborhood levels.

## 7.2 Multilevel Regression Model

The multilevel regression model for this research is expanded from linear regression models by specifying intercepts and slopes as random parameters for each of the groups. The Level-1 (individual-level) model includes the household characteristic variables, which estimate effects on operational energy consumption at the individual household level. The intercept and slopes in the Level-1 model are further defined in the Level-2 (group-level) model by the neighborhood characteristic variables, which illustrate effects at the group level (see Equations 7-5 and 7-6).

### Level-1:

$$Y_{ij} = \beta_{0j} + \sum_{i=1}^k \beta_{ij}x_{ij} + r_{ij} \quad (7-5)$$

Where:

- $Y_{ij}$  is the dependent variable for individual  $i$  in group  $j$ ;
- $\beta_{0j}$  is the intercept for group  $j$  that is further explained by Level-2 variables in Equation 7-6;
- $\beta_{ij}$  is the slope for independent variable  $x_{ij}$ , and will also be further explained by group-level variables in the Level-2 equation (Equation 7-7);
- $x_{ij}$  is the Level-1 independent variable for individual  $i$  in group  $j$ ;
- $r_{ij}$  is the error term for individual  $i$  in group  $j$ ;  $r_{ij} \sim N(0, \sigma)$ .

## Level-2:

$$\beta_{0j} = \gamma_{00} + \sum_{j=1}^m \gamma_{0j} Z_{0j} + u_{0j} \quad (7-6)$$

$$\beta_{ij} = \gamma_{i0} + \sum_{j=1}^m \gamma_{ij} Z_{ij} + u_{ij} \quad (7-7)$$

Where:

- $\gamma_{00}$  and  $\gamma_{i0}$  are the expected slopes for the corresponding group with zero values of Level-2 variables;
- $\gamma_{0j}$  and  $\gamma_{ij}$  are the coefficients with the mean values of Level-2 variables;
- $Z_{0j}$  and  $Z_{ij}$  are the Level-2 independent variables for group  $j$ ;
- $u_{0j}$  and  $u_{ij}$  are the random effect residuals for the corresponding group;  $u_{0j}, u_{ij} \sim N(0, \tau)$ .

I use Hierarchical Linear and Nonlinear Modeling (HLM) as the computation software for this study. Through maximum likelihood estimation, HLM calculates the estimated values for all parameters. It presents the correlations between dependent variables and Level-1 and Level-2 variables, and reveals the cross-level interactions where Level-1 variables transfer their effects on dependent variables through Level-2 variables.

### 7.2.1 Level-1 Model: Household Characteristics

The first level in the multilevel regression is a linear regression model in which household operational energy consumption is explained by a set of household socio-economic and demographic characteristics (household income, household size, household structure, and home ownership), dwelling unit physical attributes (unit area and whether or not located on the top floor), appliance ownership (air conditioner and solar water heater), and usage control (usage or not of electric heating).

User attitude and behavior of appliance usage may have a significant impact on operational energy consumption. However, due to the inconsistency of the household survey questionnaires that were designed by two different teams over the two years, there are no questions on household attitudes towards in-home energy-saving behaviors that were asked in both years. Thus, unfortunately, this study is unable to include any variables that describe user attitudes and occupant behavior. In addition, as discussed in Chapter 3, the households' self-reported utility

bills deviates from the actual energy consumption data, which results in inaccurate measurement of the dependent variable. The omitted user attitude variables may lead to endogeneity in the model and the measurement error in energy consumption may lead to larger standard errors.

With all individual-level variables that have been defined in Chapter 3, the Level-1 equation is expressed as Equation 7-8:

$$\begin{aligned} \text{LN\_TMJ}_{ij} = & \beta_{0j} + \beta_{1j}\text{LN\_HHINC}_{ij} + \beta_{2j}\text{ADULT\_2}_{ij} + \beta_{3j}\text{ADULT\_3}_{ij} + \beta_{4j}\text{CHILD}_{ij} \\ & + \beta_{5j}\text{ELDERLY}_{ij} + \beta_{6j}\text{RENTAL}_{ij} + \beta_{7j}\text{TOPFLOOR}_{ij} + \beta_{8j}\text{LN\_AREA}_{ij} + \beta_{9j}\text{AC\_1}_{ij} \\ & + \beta_{10j}\text{AC\_2}_{ij} + \beta_{11j}\text{SOLWH}_{ij} + \beta_{12j}\text{ELECHEAT}_{ij} + r_{ij} \end{aligned} \quad (7-8)$$

Where:

- LN\_TMJ is the natural log of household total operational energy consumption (including electricity, gas, and coal but excluding centralized heating);
- LN\_HHINC is the natural log of household income;
- ADULT\_2 and ADULT\_3 are dummy variables indicating whether there are two or three adults in the household (yes=1 and no=0);
- CHILD and ELDERLY are dummy variables indicating whether there is a child or elderly in the household (yes=1 and no=0);
- RENTAL is a dummy variable indicating whether the unit is a rental unit (yes=1 and no=0);
- TOPFLOOR is a dummy variable indicating whether the unit is on the top floor of the residential building (yes=1 and no=0);
- LN\_AREA is the natural log of unit area;
- AC\_1 is a dummy variable indicating whether the household own one air-conditioner;
- AC\_2 is a dummy variable indicating whether the household own two or more than two air-conditioner;
- SOLWH is a dummy variable indicating whether the household own solar water heater;
- ELECHEAT is a dummy variable indicating whether the unit uses electric heating (yes=1 and no=0);

Before conducting multilevel regression analysis, I center all independent variables in order to clarify interpretation of regression coefficients and to avoid potential multicollinearity problems in the model through reducing the covariance between the intercepts and slopes (Cronbach, 1987; Hofmann and Gavin, 1998; Gujarati, 2003; Preacher, 2003). There are two typical centering methods that are widely practiced—grand-mean centering, which subtracts the mean of the entire sample from each individual-level variable, and group-mean centering, which subtracts the mean of the corresponding group from each individual-level variable. Though these two methods are not entirely equivalent, both are statistically appropriate for this study. In the case where there is no particular reason to favor either method, I apply the grand-mean centering to all variables since it is simpler, more commonly employed, and recommended by scholars (Snijders and Bosker, 1999; Hox, 2002; Luke, 2004; Bickel, 2007).

To replace the raw values of the independent variables with the differences between the raw values and the grand mean, the formula can be rewritten as Equation 7-9:

$$\begin{aligned}
 \text{LN\_TMJ}_{ij} = & \beta_{0j} + \beta_{1j}(\text{LN\_HHINC}_{ij} - \overline{\text{LN\_HHINC}}) + \beta_{2j}(\text{ADULT\_2}_{ij} - \overline{\text{ADULT\_2}}) \\
 & + \beta_{3j}(\text{ADULT\_3}_{ij} - \overline{\text{ADULT\_3}}) + \beta_{4j}(\text{CHILD}_{ij} - \overline{\text{CHILD}}) + \beta_{5j}(\text{ELDERLY}_{ij} \\
 & - \overline{\text{ELDERLY}}) + \beta_{6j}(\text{RENTAL}_{ij} - \overline{\text{RENTAL}}) + \beta_{7j}(\text{TOPFLOOR}_{ij} - \overline{\text{TOPFLOOR}}) \\
 & + \beta_{8j}(\text{LN\_AREA}_{ij} - \overline{\text{LN\_AREA}}) + \beta_{9j}(\text{AC\_1}_{ij} - \overline{\text{AC\_1}}) + \beta_{10j}(\text{AC\_2}_{ij} - \overline{\text{AC\_2}}) \\
 & + \beta_{11j}(\text{SOLWH}_{ij} - \overline{\text{SOLWH}}) + \beta_{12j}(\text{ELECHEAT}_{ij} - \overline{\text{ELECHEAT}}) + r_{ij}
 \end{aligned}
 \tag{7-9}$$

Where:

- The second variables in the parentheses (with bars over them) represent the grand means of the first variables in the parentheses respectively.
- For example,  $\overline{\text{LN\_HHINC}}$  is the grand mean of LN\_HHINC, etc.

### 7.2.2 Level-2 Model: Neighborhood Characteristics

The multilevel regression model's second level is designed to further explain the intercept and slopes of the first level model by group-level variables. The neighborhood form variables

included in the second-level model are: density (floor area ratio, FAR), mixed use (building function mix, BFM), solar gain (summer solar gain index, SSG), and wind flow (porosity, POR).

Similar to the Level-1 model, I apply the group-mean centering technique to the Level-2 model. The regression formula is expressed as Equation 7-10:

$$\beta_{ij} = \gamma_{i0} + \gamma_{i1}(\text{FAR}_i - \overline{\text{FAR}}) + \gamma_{i2}(\text{BFM}_i - \overline{\text{BFM}}) + \gamma_{i3}(\text{SSG}_i - \overline{\text{SSG}}) + \gamma_{i4}(\text{POR}_i - \overline{\text{POR}}) + u_{ij}$$
$$i = 0, 1, 2, \dots, 12 \quad (7-10)$$

### 7.2.3 Results: Significant Household, Neighborhood, and Interaction Effects

I use HLM to acquire the results of this multilevel regression model through maximum likelihood estimation (see Table 7 - 2).

**Table 7 - 2 Maximum Likelihood Estimation of  
Multilevel Regression Model Results**

Fixed Effect		Co-efficient	Std. Err.	P-Value	Fixed Effect		Co-efficient	Std. Err.	P-Value
<b>For INTC., <math>\beta_{0j}</math></b>					<b>For LL_HHINC slope, <math>\beta_{1j}</math></b>				
INTC.	$\gamma_{00}$	<b>10.374</b>	<b>0.034</b>	<b>0.000</b>	INTC.	$\gamma_{10}$	<b>0.096</b>	<b>0.018</b>	<b>0.000</b>
FAR	$\gamma_{01}$	<b>-0.144</b>	<b>0.063</b>	<b>0.035</b>	FAR	$\gamma_{11}$	0.043	0.039	0.284
<i>BFM</i>	$\gamma_{02}$	<b>0.438</b>	<b>0.223</b>	<b>0.065</b>	<i>BFM</i>	$\gamma_{12}$	<b>-0.312</b>	<b>0.129</b>	<b>0.026</b>
SSG	$\gamma_{03}$	0.361	0.358	0.326	SSG	$\gamma_{13}$	-0.093	0.183	0.615
POR	$\gamma_{04}$	-0.530	0.451	0.255	POR	$\gamma_{14}$	0.129	0.253	0.616
<b>For ADULT_2 slope, <math>\beta_{2i}</math></b>					<b>For ADULT_3 slope, <math>\beta_{3i}</math></b>				
INTC.	$\gamma_{20}$	0.115	0.067	0.101	INTC.	$\gamma_{30}$	<b>0.231</b>	<b>0.091</b>	<b>0.020</b>
FAR	$\gamma_{21}$	-0.109	0.125	0.397	FAR	$\gamma_{31}$	-0.116	0.184	0.536
BFM	$\gamma_{22}$	0.167	0.451	0.714	BFM	$\gamma_{32}$	0.082	0.594	0.892
SSG	$\gamma_{23}$	-0.216	0.693	0.759	SSG	$\gamma_{33}$	-0.195	0.861	0.823
POR	$\gamma_{24}$	-0.820	0.854	0.350	POR	$\gamma_{34}$	-0.923	1.213	0.456
<b>For CHILD slope, <math>\beta_{4j}</math></b>					<b>For ELDERLY slope, <math>\beta_{5j}</math></b>				
INTC.	$\gamma_{40}$	<b>0.133</b>	<b>0.032</b>	<b>0.001</b>	INTC.	$\gamma_{50}$	0.007	0.062	0.918
FAR	$\gamma_{41}$	-0.004	0.060	0.949	FAR	$\gamma_{51}$	-0.013	0.134	0.924
BFM	$\gamma_{42}$	0.320	0.217	0.158	BFM	$\gamma_{52}$	0.317	0.402	0.441
SSG	$\gamma_{43}$	0.292	0.335	0.395	SSG	$\gamma_{53}$	-0.108	0.548	0.847
POR	$\gamma_{44}$	0.321	0.429	0.464	POR	$\gamma_{54}$	-0.277	0.889	0.759
<b>For RENTAL slope, <math>\beta_{6j}</math></b>					<b>For TOPFLOOR slope, <math>\beta_{7j}</math></b>				
INTC.	$\gamma_{60}$	-0.040	0.056	0.486	INTC.	$\gamma_{70}$	-0.036	0.041	0.393
FAR	$\gamma_{61}$	0.045	0.105	0.672	FAR	$\gamma_{71}$	-0.046	0.080	0.574
<i>BFM</i>	$\gamma_{62}$	<b>-0.725</b>	<b>0.363</b>	<b>0.061</b>	BFM	$\gamma_{72}$	0.468	0.273	0.103
SSG	$\gamma_{63}$	0.261	0.573	0.654	SSG	$\gamma_{73}$	0.499	0.401	0.229
POR	$\gamma_{64}$	1.229	0.750	0.118	<b>POR</b>	<b><math>\gamma_{74}</math></b>	<b>1.745</b>	<b>0.548</b>	<b>0.006</b>
<b>For LN_AREA slope, <math>\beta_{8i}</math></b>					<b>For AC_1 slope, <math>\beta_{9i}</math></b>				
INTC.	$\gamma_{80}$	<b>0.298</b>	<b>0.061</b>	<b>0.000</b>	INTC.	$\gamma_{90}$	<b>0.229</b>	<b>0.052</b>	<b>0.000</b>
FAR	$\gamma_{81}$	0.059	0.109	0.597	FAR	$\gamma_{91}$	-0.054	0.099	0.591
<i>BFM</i>	$\gamma_{82}$	<b>-0.823</b>	<b>0.404</b>	<b>0.056</b>	BFM	$\gamma_{92}$	0.086	0.324	0.793
SSG	$\gamma_{83}$	-0.340	0.644	0.603	SSG	$\gamma_{93}$	0.235	0.513	0.651
POR	$\gamma_{84}$	0.184	0.756	0.810	POR	$\gamma_{94}$	0.350	0.645	0.593
<b>For AC_2 slope, <math>\beta_{10j}</math></b>					<b>For SOLWH slope, <math>\beta_{11j}</math></b>				
INTC.	$\gamma_{100}$	<b>0.278</b>	<b>0.056</b>	<b>0.000</b>	<i>INTC.</i>	$\gamma_{110}$	<b>-0.087</b>	<b>0.045</b>	<b>0.071</b>
FAR	$\gamma_{101}$	0.078	0.110	0.485	FAR	$\gamma_{111}$	-0.070	0.083	0.409
BFM	$\gamma_{102}$	-0.020	0.361	0.958	BFM	$\gamma_{112}$	0.028	0.276	0.920
SSG	$\gamma_{103}$	-0.194	0.570	0.737	SSG	$\gamma_{113}$	0.035	0.438	0.937
POR	$\gamma_{104}$	0.042	0.752	0.956	POR	$\gamma_{114}$	0.325	0.618	0.605
<b>For ELECHEAT slope, <math>\beta_{12j}</math></b>									
INTC.	$\gamma_{120}$	-0.004	0.053	0.942					
FAR	$\gamma_{121}$	0.187	0.088	0.147					
BFM	$\gamma_{122}$	-0.484	0.285	0.106					
SSG	$\gamma_{123}$	-0.187	0.372	0.621					
<b>POR</b>	$\gamma_{124}$	<b>1.083</b>	<b>0.459</b>	<b>0.030</b>					

$N_1=3838, N_2=23, R_1^2=0.363; p<0.05; p<0.10$

Source: Author



The estimated coefficients suggest that several household, neighborhood, and interaction effects have positive or negative impacts on operational energy consumption at a significance level of 0.05 or 0.10. The summarized information is presented in Table 7 - 3.

**Table 7 - 3 Household, Neighborhood and Interaction Effects on Operational Energy Consumption in Jinan**

	<i>Household Effects</i>	<b>FAR</b>	<b>BFM</b>	<b>SSG</b>	<b>POR</b>	<i>Interaction Effects</i>
<i>Neighborhood Effects</i>		– *	+	n.s.	n.s.	
<b>LN_HHINC</b>	+ *	n.s.	– *	n.s.	n.s.	
<b>ADULT_2</b>	n.s.	n.s.	n.s.	n.s.	n.s.	
<b>ADULT_3</b>	+ *	n.s.	n.s.	n.s.	n.s.	
<b>CHILD</b>	+ *	n.s.	n.s.	n.s.	n.s.	
<b>ELDERLY</b>	n.s.	n.s.	n.s.	n.s.	n.s.	
<b>RENTAL</b>	n.s.	n.s.	–	n.s.	n.s.	
<b>TOPFLOOR</b>	n.s.	n.s.	n.s.	n.s.	+ *	
<b>LN_AREA</b>	+ *	n.s.	–	n.s.	n.s.	
<b>AC_1</b>	+ *	n.s.	n.s.	n.s.	n.s.	
<b>AC_2</b>	+ *	n.s.	n.s.	n.s.	n.s.	
<b>SOLWH</b>	–	n.s.	n.s.	n.s.	n.s.	
<b>ELECHEAT</b>	n.s.	n.s.	n.s.	n.s.	+ *	

+ \*, – \*: significant positive or negative correlation at a significance level of 0.05 (p<0.05)

+, –: significant positive or negative correlation at a significance level of 0.10 (p<0.10)

n.s.: not significant

*Source: Author*

### 7.3 Analysis of Multilevel Regression Results

The interpretation of multilevel regression results is similar to that of ordinary least squares (OLS) regression models. The estimated coefficients suggest the correlations between the

independent variable and the dependent variable, while the p-values indicate whether those correlations are significantly different from zero. The household and neighborhood effects directly reflect the correlations, while the interaction effects explain the effect of neighborhood characteristics as transferred through household characteristics.

All independent variables have been transformed through grand-mean centering; therefore, the coefficient  $\gamma_{00}$  is the intercept that indicates the natural logged operational energy efficiency for an “average” household who has exactly average values for all household and neighborhood characteristics (and thus all subsequent independent variables are zero). The estimated value of this coefficient, 10.379, means that such “average” household consumes  $e^{10.379}$ , i.e. 32,177 MJ of operational energy annually.

Moreover, the dependent variable is transformed into its natural log form; therefore, the coefficient indicates that one unit change in the independent variable is associated with  $(e^{\text{coefficient}} - 1) \times 100\%$  change in the dependent variable. Since most coefficients are very small,  $(e^{\text{coefficient}} - 1)$  is approximate to the value of the coefficient itself. As a result, other than for a few exceptionally large coefficients, it is usually legitimate to directly use the coefficient as the percentage change in the household operational energy consumption correlated with one unit change in the independent variable.

### 7.3.1 Effects of Household Characteristics

The multilevel regression results suggest that six household characteristics have a significant positive correlation with operational energy consumption, including variables depicting socio-economic and demographic characteristics (household income, presence of three or more adults, and presence of a child), dwelling physical attributes (natural log of unit area) and appliance ownership (ownership of one or more air conditioners).

Households with higher income are expected to consume more operational energy holding other variables constant. Since in the multilevel regression model, both total operational energy consumption and household income are both natural logged, the estimated coefficient ( $\gamma_{10}=0.096$ ) suggests the income elasticity of operational energy consumption. *Ceteris paribus*, for each 1% increase in household income, the operational energy consumption is estimated to grow by 0.096%. The effect of household income on operational energy consumption, though significant,

is strikingly small. That is possibly because the higher energy consumption can be mostly attributed to other household effects, which will soon be discussed in subsequent paragraphs, instead of the higher household income itself.

In terms of household size and structure, consistent with intuition, households with two or more adults are also likely to be larger operational energy consumers. The regression results suggest that households having three or more adults ( $\gamma_{30}=0.231$ ) consume 23.1% more operational energy than those with exactly the same characteristics yet having only one adult. Similarly, having a child in the household ( $\gamma_{40}=0.133$ ) also yields to approximately 13.3% more energy consumption than households without a child; however, the presence of the elderly does not have a significant impact. There are two reasons for the positive contribution to operational energy consumption by household size and structure. First, larger household, especially those with a larger number of adults, leads to greater energy demand for daily household operational activities such as cooling, lighting and cooking. Second, the presence of a child is likely to increase the time that the household, or at least some of the household members, spends at home for caretaking duties. That leads to higher energy consumption, especially over the summer when the child is in school vacation.

As expected, the unit area of the dwelling has a significantly positive correlation with the energy usage. The estimated coefficient ( $\gamma_{80}=0.298$ ) also depicts the elasticity between unit area and energy consumption, as both variables are included in the natural log form. Larger housing units require more energy for lighting and cooling, as evidenced by the estimation that 1% increase in unit area is associated with 0.298% more annual operational energy consumption. Larger unit areas result from a larger number of rooms and/or the increased size of rooms. Either of these characteristics can cause higher energy consumption for lighting, cooling and heating purposes. Moreover, it is important to note that the effect of dwelling unit area is larger than that of household income. It suggests that in the Chinese context, the increasing living area may have a larger impact on operational energy consumption than the rising household income level.<sup>6</sup>

---

<sup>6</sup> It is important to note that dwelling unit space may also be the cascading effect of household income, i.e. households with higher income purchase larger dwellings. In this multilevel regression model, such effect is not strictly controlled. A multi-stage model may be able to address this concern, and will be further discussed in Chapter 8. The same effect may also exist between air condition ownership and household income.

Appliance ownership is another significant factor influencing household operational energy consumption. In the multilevel regression results, households owning one or more than one air conditioners, respectively, consume 22.9% and 27.8% more energy than those who do not ( $\gamma_{90}=0.229$ ;  $\gamma_{100}=0.278$ ). On the other hand, possessing a solar water heater is slightly associated with less operational energy consumption ( $\gamma_{110}=-0.087$ ), but that correlation is only significant at  $p<0.071$  (about 93% confidence level). Since air conditioners and solar water heaters are the only two appliances surveyed in both years, I cannot estimate the relationship between energy consumption and the ownership of other appliances.

As concluded from the above results, households with higher incomes, presence of more than three adults or a child, larger dwellings, and ownership of one or more air conditioners are more likely to consume more operational energy per year. These conclusions generally support the hypothesis that households with higher socio-economic status are the larger energy consumers in the residential sector in China.

### 7.3.2 Effects of Neighborhood Characteristics

Among the four neighborhood-level variables included in the multilevel regression model, floor area ratio is the only one found to have a direct significant correlation with household operational energy consumption. Building function mix may have a slightly positive correlation with household operational energy consumption, but the correlation is only significant at a confidence level of about 93.5%. I do not find strong evidence to support that summer solar gain index and porosity have significant direct impacts; however, some of the urban form characteristics are associated with energy consumption indirectly through cross-level interactions further explained in detail in the subsequent section.

Floor area ratio is found to have a significant negative correlation with household operational energy consumption, when all other household and neighborhood variables are held constant. The regression results show that households living in neighborhoods with higher floor area ratios are likely to use less energy than those who live in less dense neighborhoods ( $\gamma_{01}=-0.144$ ).

As shown in Chapter 6, taken on its own, floor area ratio is associated with higher operational energy use. However, that bivariate result changes once accounting for the characteristics of the households in neighborhoods with higher floor area ratios, which are primarily superblocks. In

other words, what the Level-2 model results here suggest is that for two households, with all other characteristics identical, living in two neighborhoods with different floor area ratios, the household living in the neighborhood with higher floor area ratios would be expected to consume less energy than the other household.

This result provides evidence that urban residential neighborhoods with higher density are less energy intensive per household. This can be explained by the fact that, with an equal number of housing units, higher-density neighborhoods have lower needs for heating and cooling consumption since they have higher portions of shared walls and smaller exterior wall surface areas. This is consistent with previous research conducted in other contexts suggesting that high-density and compact residential neighborhoods are more energy efficient (Stone and Rogers, 2001; Norman et al., 2006; Ewing and Rong, 2008; Kockelman et al., 2011).

The Level-2 results also hint that households living in neighborhoods with higher building function mix may be slightly more likely to consume more operational energy ( $\gamma_{02}=0.438$ ). The p-value of 0.065 is close to passing the standard significance test (a level of 0.05). This result is consistent with research showing that mixed-use apartment complexes consume more operational energy than general residential buildings because the more active heat management of mixed-use buildings can result in higher cooling load in the summer (Choi et al., 2012). Still, this result warrants further investigation.

### **7.3.3 Cross-Level Interaction Effects**

Other than the direct effects of household and neighborhood characteristics, multilevel regression analysis also reveals the indirect cross-level interaction effects as some neighborhood-level variables transfer their effects on operational energy consumption through interactions with household-level characteristics.

As discussed, on its own, building function mix has a marginally significant positive correlation with household operational energy consumption; however, it imposes a significant impact on the slope of household income in the regression model ( $\gamma_{12}=-0.312$ ). The result indicates that the positive effect of household income on operational energy consumption is lessened for households living in neighborhoods with higher building function mix. To be more specific, one

percentage point increase in the building function mix of the neighborhood is expected to reduce the household income's positive effect on operational energy consumption by 0.312%.

One possible explanation for this interaction effect between building function mix and household income is that higher-income households may tend to spend less time inside their homes in more mixed-use neighborhoods. In neighborhoods with higher building function mix, it is much more convenient for households to go dining, shopping or enjoying entertainment activities without traveling far away. For households with higher income and thus greater purchasing power, the availability of neighborhood amenities is likely to attract them to spend more time out of their homes, and thus to consume less operational energy at home. Therefore, while building function mix may increase operational energy consumption for all households, the higher household income could reduce this positive correlation as the wealthier households may be enticed out of home more often.

Building function mix may also have a negative effect on operational energy consumption of households living in rental units, but that effect is only significant at a significance level of  $p < 0.061$  ( $\gamma_{62} = -0.725$ ). Households living in rental housing may choose to avoid big investment in their units, especially non-necessities such as large home entertainment products. If living in a more mixed-use neighborhood, households in rental units may be more attracted to spend time outside home, for entertainment purposes for instance, and this may explain the slight interaction effect between building function mix and rental units.

Porosity is the other neighborhood variable that transfers its effect through cross-level interaction. Households who live on the top floor of buildings and/or who have electric heating *and* live in neighborhoods with high porosity would be expected to have higher energy consumption ( $\gamma_{74} = 1.745$ ;  $\gamma_{124} = 1.083$ ). In other words, a one percentage point increase in the porosity of the neighborhood is expected to boost the top-floor and electric-heating effects on operational energy consumption by 1.745% and 1.083%, respectively.

The positive effect of porosity on operational energy consumption through its interaction with top floor living and electric heating likely results from greater demand for heating. Wind can more easily penetrate through a more porous neighborhood, thus leading to greater losses of heat through building exterior walls. This effect is more evident for homes on the top floor of

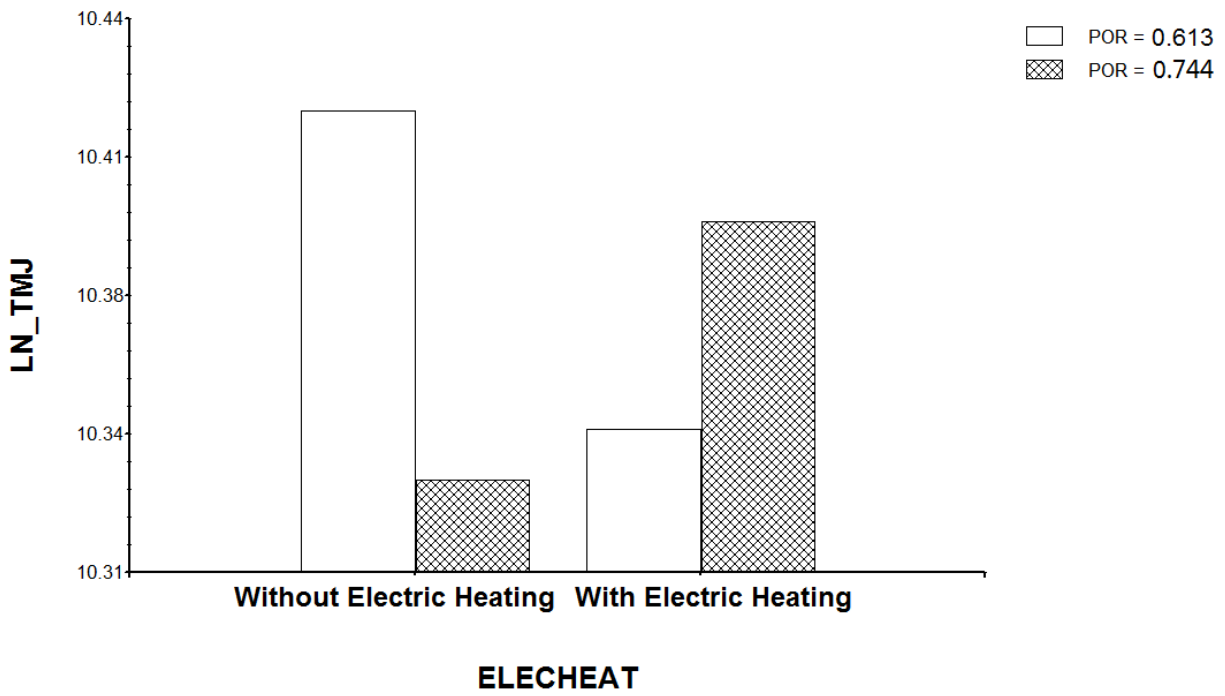
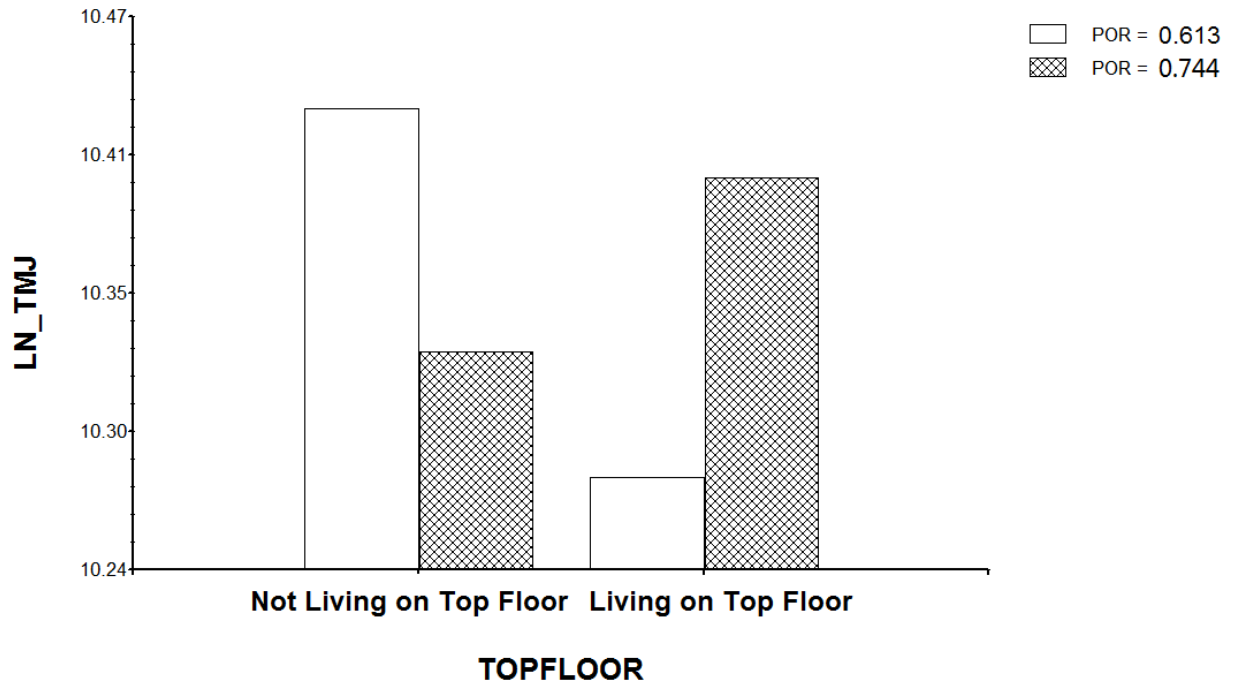
buildings because the total area of exposed surface in these units is larger when the roofs are included. The higher consumption of electric, natural gas and coal for the purpose of heating is documented in this interaction effect. As a result, households are likely to consume more operational energy when living on top floors and/or to use their electric heating more intensively if living in neighborhoods with higher porosity.

#### **7.3.4 Visualization of Interaction Effects**

I plot two significant interactions, POR with TOPFLOOR and POR with ELECHEAT, to visualize the household, neighborhood, and interaction effects on operational energy consumption together. Figure 7 - 1 shows the degree to which porosity exerts its effect on operational energy consumption through its interaction with the two household variables.

The figures representing LN\_TMJ on the Y-axis are the natural logged total energy consumption data. I choose two values of porosity representing the 25th and 75th percentiles of the variable.

**Figure 7 - 1 Visualization of Interaction Effects**



*Source: Author*



The interaction effect is represented by the comparison of the two bars with the same color. Taking the upper diagram as an example, the two white bars show that in neighborhoods with lower-than-average porosity (0.613), households living on the top floor consume less energy than those who do not. However, the two shaded bars suggest that in those neighborhoods with higher-than-average porosity (0.744), top-floor households have higher operational energy consumption instead. Such a shift is attributed to the positive cross-level interaction effect between porosity and top floor variables, which is strong enough to switch the effects of household variables on energy consumption. The lower diagram displays the similar relationship between porosity and presence of electric heating.

To conclude, the multilevel regression analysis reveals that total operational energy consumption is characterized by household, neighborhood, and interaction effects. For household characteristics, higher household income, presence of three or more adults or a child, larger unit area, and ownership of one or more air conditioners are found to have significant positive correlation with operational energy consumption. In terms of neighborhood characteristics, higher density (floor area ratio) is strongly associated with more energy usage. The interaction effects are more complex as neighborhoods characteristics transfer their impact on operational energy consumption through household characteristics. On the one hand, higher neighborhood building function fix decreases the positive correlation between household income and energy consumption. On the other hand, higher neighborhood porosity significantly increases the energy consumption of households living on the top floor or with electric heating.

In Chapter 8, I will conclude this thesis by summarizing the key findings of this research, elaborating the implications and policy recommendations for improving operational energy efficiency in China's residential sector, and discussing the strengths and limitations of this study and potential topics for future research.

## **Chapter 8: Conclusion and Discussion**

Under the broad picture of China's soaring energy consumption growth in the residential sector and its ambitions to achieve energy conservation and emissions reductions over the next decades, I take eastern China's Jinan as the case to analyze the household operational energy consumption in urban China. Based on empirical data from a survey of approximately 4,000 urban households and spatial analysis of 23 residential neighborhoods in Jinan, I conduct descriptive analysis and apply multilevel regression modeling techniques to investigate the household, neighborhood, and cross-level interaction effects on operational energy consumption.

In this chapter, I will summarize the major conclusions and policy implications from this research, discuss the limitations, and propose directions for future research.

### **8.1 Conclusions**

The major conclusions drawn from this research cover three areas: patterns of household operational energy consumption, variations of household and neighborhood characteristics, and evidence of household, neighborhood, and interaction effects on operational energy consumption in Jinan.

#### **8.1.1 Patterns of Household Operational Energy Consumption**

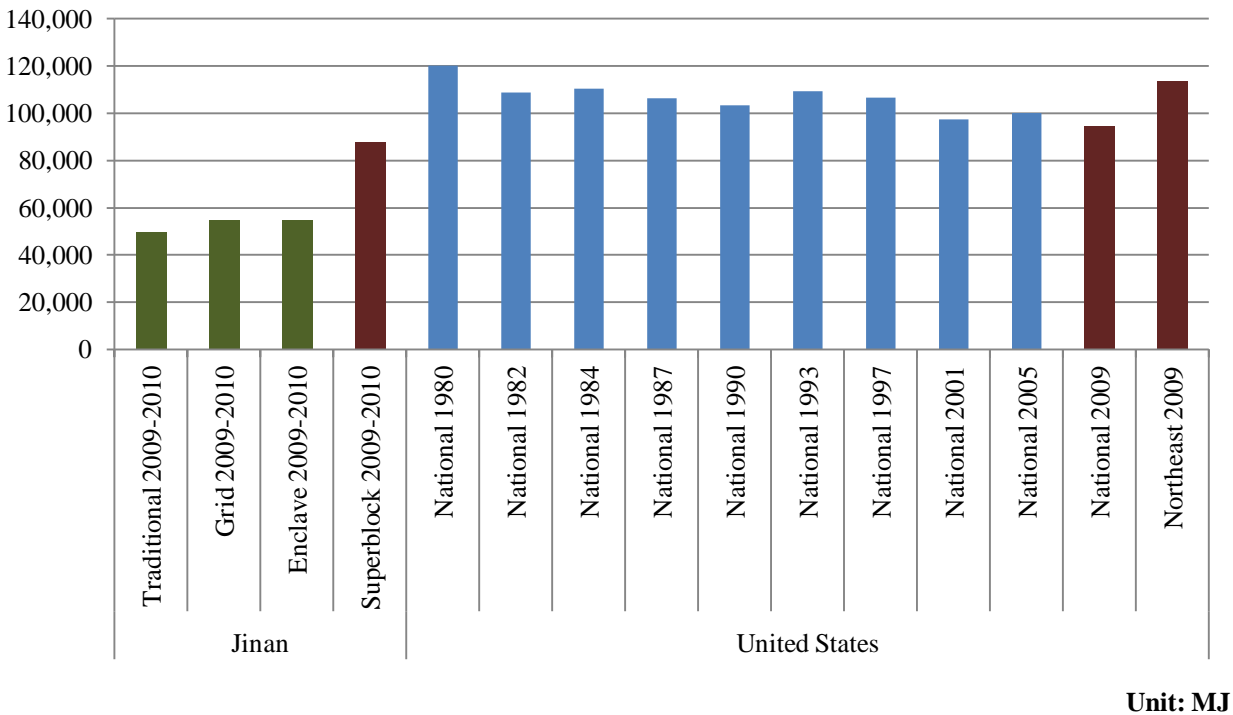
Using the self-reported data on utility bills and dwelling unit construction areas, I estimate the operational energy consumption of the valid 3,831 households from 23 neighborhoods covered in the survey. The results suggest several key findings highlighting the operational energy consumption patterns in Jinan.

First, operational usage accounts for a predominantly large portion of total residential energy consumption. Within the total energy uses of the surveyed households, roughly three quarters are attributable to operational energy consumption, while common area, transportation, and embodied energy consumption only account for a 25% share. This indicates that in-home activities, such as heating, cooling, cooking, lighting, and entertainment, are still the major purposes of energy consumption for Jinan households. The large share of the operational category reveals the large potential to reduce Jinan households' total energy consumption by increasing operational energy efficiency.

Second, households living in different typologies of neighborhoods vary dramatically in operational energy consumption patterns. The superblock households in the survey consume 50% more operational energy than those living in traditional, grid and enclave neighborhoods on a per household basis, but have slightly lower per square meter operational energy consumption. Differences are also found in energy source shares due to the availability of energy usage options. Electricity accounts for half of the total operational energy consumption in all households; however, the households in traditional neighborhoods use significantly more coal while those in superblock neighborhoods consume much more energy for centralized heating. Such types of operational energy consumption patterns reflect the coexistence of multiple residential neighborhood typologies in Jinan, and suggest that the promotion of operational energy efficiency should also address the great variety of housing stock.

Third, the annual operational energy consumption of Jinan's superblock households, which reaches as high as almost 90,000 MJ per year on average, is not far behind the levels in some developed countries. For example, Figure 8 - 1 compares the annual operational energy consumption of Jinan with US households in 2009. Already, the energy consumption of Jinan's superblock households exceeds 90% of the household average in the United States. Comparing Jinan with the Northeast US, where the climate patterns are more similar, the households in Jinan's superblock neighborhoods consume more than three quarters of the operational energy used by their US counterparts annually. Such levels of energy usage are striking and deserve greater attention, even though households in the other three neighborhood typologies have much lower operational energy consumption. As China's household income level and urban lifestyle continue to improve, operational energy consumption may well reach, or even surpass, the levels in the United States and other developed countries without effective measures to realize greater energy efficiency in the residential sector.

**Figure 8 - 1 Comparison of Annual Household Operational Energy Consumption between Jinan and the United States**



Source: Author and U.S. Energy Information Administration, 2010

### 8.1.2 Variations of Household and Neighborhood Characteristics

Based on the survey data, I summarized four groups of key household characteristics, including socio-economic status, physical attributes, appliance ownership, and usage control. Similarly, four key neighborhood characteristics – density, mixed use, solar gain, and wind flow – were also derived from the geographic information analysis of the selected neighborhoods. The examination of these data affirms that, even though neighborhoods within the same typology group tend to share similar household and neighborhood characteristics, variation still largely exists across different typologies.

The differences in household characteristics indicate that, with China’s economic growth and social transformation, disparities begin to emerge and become more pronounced in the urban population. Among all the households responding validly to the survey, those living in the traditional neighborhoods represent one extreme on most characteristics, including the lowest household income, the smallest household size, the lowest homeownership ratio, the smallest

dwelling size, the lowest percentage of air conditioner ownership, and the highest coverage of electric heating due to the lack of access to centralized heating. On the other extreme, the superblock neighborhoods tend to have exactly the opposite household characteristics to the traditional neighborhoods. The grid and enclave neighborhoods fall in between. Such patterns may suggest some evidence of residential segregation in Jinan as different social classes are spatially agglomerated in separate residential neighborhoods.

The variation in neighborhood characteristics is more complicated. The superblock typology seems to be an outlier in almost all dimensions, with: the highest floor area ratio, the lowest building function mix, the lowest summer solar gain index, and the highest porosity index. These characteristics are associated with the dramatic change of China's housing policy which transformed housing from state welfare benefits to market-oriented commodities. The developers of superblock neighborhoods, the prevailing typology for China's commodity housing nowadays, attempt to realize higher profitability and cater to the needs of middle- and upper-class home buyers by pursuing high-density, gated residential neighborhoods with high-rises and internal public open space. However, the other three typologies, which were mostly designed and constructed during the public housing era, are less reflective of these design elements that aim to promote commercial profits. These neighborhoods not only significantly deviate from the superblocks, but also differentiate themselves from one another internally in terms of physical attributes.

The vast differences in household and neighborhood characteristics in Jinan indicate a complicated residential development landscape. Such diversity gives rise to greater challenges to restraining growing operational energy consumption and promoting energy efficiency in the residential domain.

### **8.1.3 Evidence of Household, Neighborhood, and Interaction Effects on Operational Energy Consumption**

Is there a connection between the patterns of Jinan's operational energy consumption and the variations of household and neighborhood characteristics? As the core component of this thesis, the multilevel regression analysis shows that operational energy consumption is related with

household and neighborhood characteristics, and reveals the specific household, neighborhood, and cross-level interaction effects on operational energy consumption.

Six household characteristics are identified as positive, statistically significant contributors to greater energy usage: higher household income, presence of three or more adults or a child, larger dwelling unit area, and ownership of one or more air conditioners.

Among neighborhood effects, higher floor area ratio is found to associate with lower operational energy consumption. With higher portions of shared walls, neighborhoods with higher density are expected to reduce household energy losses due to heating and cooling.

In terms of cross-level interaction effects, a higher building function mix may weaken the positive effect of household income on operational consumption. For households with higher income, the availability of neighborhood amenities in mixed-use neighborhoods may attract them to spend more time out of their homes, and thus to consume less operational energy at home. Porosity is also correlated with higher energy consumption for households living on top floors or with electric heating. The increased waste of heat loss through exposure to wind penetration in more porous neighborhoods may lead to higher household energy consumption for heating. Both of these apparent interactions warrant further investigation.

These findings help to unfold the complex relationships between operational energy consumption and its influencing factors. Generally, the household effects are associated with higher socio-economic status and more affluent lifestyles. In particular, larger housing units and more home appliances, including air conditioners, are becoming more popular among Chinese households as their purchasing power and desires to pursue higher levels of living comfort grow. As China's economy steadily develops, the continued growth of household income and living standards is likely to further raise the operational energy consumption standards, following the current trend.

However, the identified neighborhood and interaction effects indicate that the current mode of residential real estate development in China can be a double-edged sword with respect to operational energy efficiency. As housing is transformed from a state welfare to a market commodity in China, the real estate developers pursue the notion of compact, gated and high-rise superblock neighborhoods so as to realize greater commercial profits. The higher floor area

ratios of these projects (compared to the traditional and enclave neighborhoods) can be beneficial to slow down the growth of operational energy consumption through the neighborhood FAR effect. On the other hand, the gated environment inhibits commercial space development inside the neighborhoods, thus lowering building function mix, and the dominance of high-rise buildings with large internal public spaces increases the porosity index. These design elements may lead to higher energy consumption through the interaction effects.

## **8.2 Policy Implications**

Faced with rapidly growing demand for energy, China has set ambitious goals for energy conservation and emissions reductions. The key findings from this research provide some evidence for future policy directions to promote energy efficiency.

### **8.2.1 More Energy-Saving Emphasis Placed on Household Operational Energy Consumption**

China has been putting most of its focus on energy efficiency policies on industrial production because the industrial sector accounts for more than 70% of the nation's total energy consumption. The government has initiated increasingly strict rules on and broad goals for reducing industrial energy waste and promoting industrial energy efficiency in the national, provincial and local development plans, regulations and policies. By adopting energy efficiency as an official development goal in its five-year plans, China has dramatically decreased its national average energy consumption per unit of GDP.

However, due to its large economic and population base, China has overtaken the United States as the world's top energy consumer. To further realize its commitment to reducing energy consumption, China has to broaden its focuses on energy efficiency, and promote energy saving measures in fields other than industrial production.

As the second biggest category for China's energy usage, the residential sector accounts for approximately 10% of the nation's annual energy consumption. Evidenced by the empirical data from the selected Jinan neighborhoods, operational energy consumption takes up a prominent portion of the total residential energy consumption. With the continued development of China's

economy and the rapid growth of living standards, operational energy consumption may further rise and pose larger challenges to China's energy efficiency goals.

Currently, limited emphasis has been placed on reducing household operational energy consumption in China. Some current measures include guidelines on home appliance energy efficiency, regulations of utility prices, and campaigns to raise awareness of energy-saving behaviors; nevertheless, many of these measures fail to effectively address the growing household operational energy consumption due to the small-scale policy coverage and the lack of strong enforcement. To further deepen the effectiveness of promoting operational energy efficiency, China needs to adopt a series of stricter and more direct policies and regulations covering a wider range of aspects concerning household operational energy consumption, including design guidelines of energy-efficiency residential neighborhoods.

### **8.2.2 Address Operational Energy Consumption in Diverse Urban Settings**

The scrutiny of Jinan's empirical data suggests that vast variations exist among different households and neighborhoods. The households vary greatly in income level, size and structure, appliance ownership, and living environment, and the neighborhoods differ from one to another in physical layout and building attributes. The highly diverse urban settings have led to very different patterns of energy consumption attitudes and behaviors. Jinan's experience is comparable to the rest of the nation. From retiree couples living in traditional courtyard houses in the old city center to young nuclear families residing in high-rise, gated communities on the outskirts, policies promoting operational energy efficiency need to address the diverse nature of urban settings in China.

For example, the available energy source options are highly divergent in different types of urban neighborhoods. The traditional neighborhoods, constructed decades, even centuries ago, often lack utility pipeline systems; therefore, coal usage is still predominant for the purposes of cooking and heating. On the other hand, coal is extinct in the superblock neighborhoods. The mostly closed internal environment in high-rises prohibits coal usage, and burning coal is also strictly banned by property management codes. The primary sources for cooking and heating in superblocks are natural gas and centralized heating systems. As a result, utility policies on



energy efficiency need to acknowledge and address the diversity of energy sources available to residents in different types of neighborhoods.

### **8.2.3 Promote Energy Efficiency while Improving Living Conditions and Comfort**

Still a developing economy, China sees strong potential opportunity for growth from its large internal demand. Many urban households expect to upgrade their levels of living comfort by moving into newer and larger homes, and every year large numbers of rural migrants come into cities seeking employment opportunities and better living conditions. Therefore, policies need to coordinate the promotion of energy efficiency and the improvement of living conditions and comfort at the same time.

The household effects identified by the multilevel analysis suggest that higher energy consumption is associated with larger household sizes and more affluent lifestyles. The continued economic transformation and growth has boosted income levels of Chinese households, prompting them to pursue higher living standards. Home appliances such as air conditioners, televisions and computers are increasing in popularity among Chinese households, and the desire for living comfort has also led to more rooms and larger sizes in newly constructed residential units. These trends all contribute to higher levels of operational energy consumption.

Higher incomes, larger residential unit sizes, and growing home appliance ownership are consequences of economic development, and are more difficult to control or regulate through policies. Attempting to solve issues of operational energy consumption by directly controlling these household characteristics may be neither practical nor sensible. A more feasible solution is to promote operational energy efficiency through the channel of impacting neighborhood or interaction effects found in this research.

### **8.2.4 Encourage Energy-Efficiency Neighborhood Design**

Operational energy efficiency has not become a primary concern for many residential real estate developers in China. First, as households are responsible for paying utility bills, developers are seldom encouraged to make energy-efficiency investments or improvements in the properties. This issue of split incentives leads to lower energy performance. Second, utility bills usually account for a small portion of households' total expenses. Many households are not concerned

with operational neighborhood energy efficiency measures when making home-buying or renting decision. Such an indifferent attitude further fosters the ignorance of, or at least disinterest in, energy efficiency in residential choices.

However, promoting energy efficiency through capitalizing on the neighborhood and interaction effects identified by this research seems to be a promising channel. Promoting compact, mixed-use and low-porosity neighborhoods may be helpful to reduce operational energy consumption, but such physical elements are not necessarily immediately desirable to real estate developers who seek maximization of profits. Policy intervention and urban design innovation are essential under such circumstances.

China can encourage energy-efficient neighborhood design through multiple ways. All urban land in China is owned by the state and leased to private developers on a leasehold system under the current land laws, hence the government has the proper legal authority and enforcement power to impose and implement policies on operational energy efficiency.

On the one hand, the government can initiate regulatory requirements to mandate more energy-efficient designs in China's residential sector. The central government can incorporate energy-efficient neighborhood guidelines into its proposed Green Energy-Efficient Building Action Plan. This compulsory policy framework can impose basic energy-saving requirements on all newly constructed residential neighborhoods. The local government can also set stricter energy efficiency requirements in land use contracts with private developers, explicitly identifying design and construction responsibilities to ensure energy performance standards.

On the other hand, the government can provide incentives to encourage real estate developers to actively pursue higher energy efficiency standards. Some possible financial tools may include tax credits, grants, rebates or loans through programs promoting energy-efficient designs for new neighborhoods or retrofits for existing neighborhoods.

### **8.3 Research Limitations and Future Directions**

Due to constraints of the survey approach, data accuracy and availability, and the research methods, this thesis has several limitations that need to be further improved in future studies.

### **8.3.1 Inconsistency of Survey**

The primary source of household data is a survey on randomly sampled households in selected Jinan neighborhoods. Due to project coordination issues, the survey approaches were slightly different over a period of two years between 2009 and 2010. This leads to some concerns that the approaches of and the results from the surveys in the two years may be inconsistent.

First, the questionnaire used in each year included a set of slightly different questions, especially in the areas of home appliance ownership and the attitudes towards energy saving. These inconsistencies resulted in the exclusion of some portions of the data in the final research.

Second, in the survey, the households were asked to provide the whole-year utility bills data to calculate operational energy consumption for the study. As a result, the survey provided utility bills data that were associated with two different years. Though the climate patterns of years 2009 and 2010 were similar, such a time difference across the surveys could still potentially lead to some inaccuracies when combining the data sets for analysis.

Future studies will be greatly improved if the data are retrieved from surveys that are consistently carried out.

### **8.3.2 Inaccuracy of Energy Consumption Data**

On the one hand, the electricity, natural gas and coal energy consumption data are calculated based on the utility bills self-reported by the households. As discussed in Chapter 4, the self-reported data are not an accurate estimation of the actual operational energy consumption. However, since not all actual energy consumption data from surveyed neighborhoods are available, using the self-reported data is the only option to conduct this study.

On the other hand, the energy consumption of centralized heating is estimated from the dwelling unit areas because heating is not metered in most neighborhoods in China. The equation that calculates centralized heating is based on an assumption that all neighborhoods have a uniform heat load index; however, due to different construction materials and building ages, heat load indices vary greatly across different settings in reality.

The replacement of estimated energy usage with actual consumption data will improve the validity of similar studies in the future.

### **8.3.3 Lack of Additional Household and Neighborhood Characteristics Data**

Besides the incomplete and inconsistent information on households' home appliance ownership and energy-saving attitudes, other critical household and neighborhood data were not included in the survey or spatial analysis.

Information on home occupancy status would be significantly helpful to reveal the connection between the time the household spends at home and the corresponding operational energy consumption. Multilevel regression analysis could also provide evidence on the household and neighborhood factors influencing the home occupancy period, which may further indirectly impact operational energy consumption. The inclusion of home occupancy period data will also be helpful to investigate the “trade-off” relationships between operational and transportation energy consumption.

In addition to refining the crude information on ownership of home appliances, the study would be further improved if the survey had collected information on the power of these appliances, as well as the usage behavior and preferences, such as frequency of usage.

The neighborhood characteristics acquired from spatial analysis are also insufficient to provide a complete picture of the physical landscape. More specific information, including the insulation and internal ventilation of buildings, may be helpful to reveal in greater detail the relationships between operational energy consumption and the neighborhood.

Moreover, it may be problematic to assign each household with the average characteristics of the entire neighborhood. The research can be further improved if households are analyzed with the characteristics of the particular location in the neighborhood they live in.

### **8.3.4 Methodological Constraints**

The multilevel regression model employed by this research is based on a group of static data. The regression results can provide some reference for designers when drafting neighborhood developments. However, in the real-world application, it is sometimes difficult or even impossible to modify one specific variable without incurring changes in other variables. For example, increasing the floor area ratio of one neighborhood design may inevitably increase its porosity as well. In other words, a neighborhood is more than simply the sum of its individual

parts. As a result, it may be difficult to know, ex-ante, whether a particular modification will truly improve energy efficiency performance of the design, based on the results of this static model only.

Similarly, as this research only focuses on operational energy consumption, the relationships revealed by the multilevel model are only applicable to operational energy consumption. Some household and neighborhood characteristics may have different impacts on common area, transportation, and embodied energy consumption. For example, higher floor area ratio may lead to lower operational energy consumption; however, the increased floors of high-rises may increase common area energy consumption for the usage of elevators and water pumps. My research alone is insufficient to address China's residential energy consumption in all aspects.

One solution to these problems is an interactive, dynamic tool which attempts to automatically capture key characteristics of neighborhood designs in real time, and reflects the impacts of design modifications holistically on all relevant characteristics. The "Making the Clean Energy City in China" project group has been building the Energy Proforma, a tool for designers and developers to observe and evaluate energy performance of neighborhood designs. After submitting required neighborhood design files through a data input interface, users are able to acquire comprehensive estimations of operational, common area, transportation and embodied energy consumption calculated by the Energy Proforma. When a modification is made, the Energy Proforma will recalculate the energy consumption data, and provide a detailed comparison of the two versions of design.

Moreover, the multilevel regression model has not resolved concerns of endogeneity. The ownership and use of appliances are related decisions made by households; however, due to the omission of appliance use, it is problematic to treat appliance ownership variables as exogenous in the regression model. Since the appliance ownership variables in the model are correlated with the error term, it could lead to the problem of endogeneity.

Zhang (2010) has attempted to solve the problem by constructing a two-stage OLS model, by treating the households' purchase choice of appliances as discrete and their consumption choice, given ownership of a set of appliances, is continuous. However, due to limitation of data availability and lack of effective instrumental variables, the results of the discrete-continuous

model were not satisfactory. Future studies, based on improved available data, could further explore more advanced modeling approaches to address the endogeneity issue.

### **8.3.5 Directions for Other Improvements**

In addition to the limitations to and potential improvements of this study, there are several areas in which similar studies in the future can make progress.

First, it would be helpful to conduct this type of research in other Chinese cities, especially those in different regions and climate zones. Though Jinan has a moderate size among the top-tier Chinese cities and a representative climate pattern of northern China, many cities are significantly different from Jinan in geographic, economic, population, and urban development aspects. Expansion of the research to other regions will be beneficial to obtaining a more comprehensive picture of household operational energy consumption in urban China.

Second, in terms of neighborhood characteristics, operational energy consumption is a complex process that is both influenced by neighborhood design and management. While this research focuses more on neighborhood characteristics in terms of physical design aspects, property operation and management are expected to have great impact on operational energy consumption as well. Future studies could incorporate characteristics of neighborhood management into the research framework.

Finally, in urban China, the promotion of operational energy efficiency largely depends on the formulation and implementation of effective public policies. The research has briefly introduced several ideas on how the Chinese government can improve residential energy performance through imposing regulations and providing incentives. Studies in the future can further compare similar residential energy efficiency policies or programs from abroad, draw experiences and lessons, and analyze the feasibility of policy options for China.

## Bibliography

- Ach ă, Carla, and Roberto Schaeffer. (2009). "Decomposition Analysis of the Variations in Residential Electricity Consumption in Brazil for the 1980–2007 Period: Measuring the Activity, Intensity and Structure effects." *Energy Policy* 37, 5208-5220.
- Bickel, Robert. (2007). *Multilevel Analysis for Applied Research: It's Just Regression!* New York: Guilford.
- ChinaToday.com. (2006). "China Province: Shandong Province." <http://www.chinatoday.com/city/shandong.htm>.
- China Meteorological Data Sharing Service System. (2012). "Data Query." [http://cdc.cma.gov.cn/shuju/index3.jsp?tpcat=SURF&dsid=SURF\\_CLI\\_CHN\\_MUL\\_MMON\\_19712000\\_CES](http://cdc.cma.gov.cn/shuju/index3.jsp?tpcat=SURF&dsid=SURF_CLI_CHN_MUL_MMON_19712000_CES).
- Choi, In Young, Sung Heui Cho, and Jeong Tai Kim. (2012). "Energy Consumption Characteristics of High-Rise Apartment Buildings According to Building Shape and Mixed-Use Development." *Energy and Buildings* 46: 123-131.
- Cronbach, L. J. (1976). "Research on Classrooms and Schools: Formulation of Questions, Design, and Analysis." (Occasional Paper, Stanford Evaluation Consortium, Stanford University.)
- Darbari, Reza Amin, and Shani Sharif. (2011). "Why Form Matters: Solar Gain and Wind Flow." (Research Report, Massachusetts Institute of Technology.)
- Darbari, Reza Amin, and Shani Sharif. (2011). "Measurement of Geometric Properties of Jinan's Neighborhood." (Research Report, Massachusetts Institute of Technology.)
- Deng, Xin. (2007). "Private Car Ownership in China: How Important is the Effect of Income?" [http://www.ecosoc.org.au/files/File/TAS/ACE07/presentations%20\(pdf\)/Deng.pdf](http://www.ecosoc.org.au/files/File/TAS/ACE07/presentations%20(pdf)/Deng.pdf).
- Density Atlas. (2012). "Introduction to Measuring Density." <http://densityatlas.org/measuring/>.
- Dubin, Jeffrey A., and Daniel L. McFadden. (1984). "An Econometric Analysis of Residential Electric Appliance Holdings and Consumption." *Econometrica*, 52(2):345-362.
- Eom, J., L.E. Clark, S.H.Kim, P. Kyle, and P.L. Patel. (2012). "China's Building Energy Use: A Long-Term Perspective based on a Detailed Assessment." (Research Report, Pacific Northwest National Laboratory.)
- Ewing, Reid, and Fang Rong. (2008). "The Impact of Urban Form on U.S. Residential Energy Use." *Housing Policy Debate*, 19(1): 1 - 27.
- General Office of the State Council. (2011). "Integrated Implementation Plan of Energy Conservation and Emissions Reductions during the 12th Five-Year Plan. (Guo-wu-yuan Guan-yu Yin-fa Shi-er-wu Jie-neng-jian-pai Zong-he-xing Gong-zuo Fang-an de Tong-zhi.)" [http://www.gov.cn/zwggk/2011-09/07/content\\_1941731.htm](http://www.gov.cn/zwggk/2011-09/07/content_1941731.htm)
- Gujarati, Damodar N. (2003). *Basic Econometrics*. New York: McGraw-Hill.
- Hox, Joop. (2002). *Multilevel Analysis: Techniques and Applications*. Mahwah: Erlbaum.
- Hofmann, David A., and Mark B. Gavin. (1998). "Centering Decisions in Hierarchical Linear Models: Implications for Research in Organizations." *Journal of Management* 24(5): 623-641.

- Huang, Youqin, and William A.V. Clark. (2002). "Housing tenure choice in transitional urban China: a multilevel analysis." *Urban Studies* 39: 7-32.
- International Energy Agency. (2010). "China Overtakes the United States to Become World's Largest Energy Consumer." [http://www.iea.org/index\\_info.asp?id=1479](http://www.iea.org/index_info.asp?id=1479).
- Jiang, Yang. "Does Energy Follow Urban Form? An Examination of Neighborhoods and Transport Energy Use in Jinan, China." (Master thesis, Massachusetts Institute of Technology.)
- Jinan Encyclopedia. (2011). "Why Are Longitude and Latitude in Jinan Different from Those on the Earth? (Jinan de Jingwei Lu Weihe yu Diqu de Xiangfan?)" <http://jinan.baik.com/article-6235.html>.
- Jinan Government. (2007). "Review of Historical Facts (Shishi Zongshu)." <http://www.jinan.gov.cn/col/col36/index.html>.
- Jinan Government. (2012). "Economic Construction (Jingji Jianshe)." <http://www.jinan.gov.cn/col/col16/index.html>.
- Kockelman, Kara M., Melissa R. Thompson, and Charlotte A. Whitehead-Frei. (2011). "Americans' Contributions to Climate Change: Opportunities for Meeting Carbon Targets." *Journal of Urban Planning and Development* 137(2): 91-100.
- Liu, Jingru, Rusong Wang and Jianxin Yang. (2005). "Metabolism and Driving Forces of Chinese Urban Household Consumption." *Population and Environment* 26(4): 325-341.
- Lollini, Barozzi, Fasano, Meroni, and Zinzi. (2006). "Optimisation of Opaque Components of the Building Envelope. Energy, Economic and Environmental Issues." *Building and Environment* 41(8): 1001-1013.
- Luke, Douglas A. (2004). *Multilevel Modeling*. Thousand Oaks: Sage.
- National Bureau of Statistics of China. (2009). *Shandong Statistical Yearbook 2009*. Beijing: China Statistics Press.
- National Bureau of Statistics of China. (2010). *China Energy Statistical Yearbook 2010*. Beijing: China Statistics Press.
- National Bureau of Statistics of China. (2011). *China Statistical Yearbook 2011*. Beijing: China Statistics Press.
- National Development and Reform Commission. (2011). "Review of Energy Conservation and Emissions Reductions in the 11th Five-Year Plan Period: Significant Achievements. (Shi-yi-wu Jie-neng-jian-pai Hui-gu: Jie-neng-jian-pai Qu-de Xian-zhu Cheng-xiao.)" [http://www.gov.cn/gzdt/2011-09/27/content\\_1957502.htm](http://www.gov.cn/gzdt/2011-09/27/content_1957502.htm).
- National Meteorological Center of China Meteorological Administration. (2012). "Jinan." <http://www.nmc.gov.cn/publish/forecast/ASD/jinan.html>.
- Ni, Meng-cheng. (2008). Motorization, Vehicle Purchase and Use Behavior in China: A Shanghai Survey. (Research Report, Institute of Transportation Studies, University of California, Davis.)



- Norman, Jonathan, Heather L. MacLean, and Christopher A. Kennedy. (2006). "Comparing High and Low Residential Density: Life - Cycle Analysis of Energy Use and Greenhouse Gas Emissions." *Journal of Urban Planning and Development*, 3: 10 - 21.
- O'Neill, Brian C., and Belinda S. Chen. (2002). "Demographic Determinants of Household Energy Use in the United States." *Population and Environment* (28): 53-88
- Ouyang, Jinlong, Jian Ge, and Kazunori Hokao. (2009). "Economic Analysis of Energy-Saving Renovation Measures for Urban Existing Residential Buildings in China Based on Thermal Simulation and Site Investigation." *Energy Policy*, 37: 140-149.
- Pachauri, Shonali. (2004). "An Analysis of Cross - sectional Variations in Total Household Energy Requirements in India Using Micro - survey Data." *Energy Policy* 32(15): 1723 - 1735.
- Pachauri, Shonali, and Leiwen Jiang. (2008). "The Household Energy Transition in India and China." *Energy Policy* 36(11): 4022-4035.
- Pletcher, Kenneth (ed.) (2011). *The Geography of China: Sacred and Historic Places*. New York: The Rosen Publishing Group.
- Preacher, Kristopher J. (2003). *A Primer on Interaction Effects in Multiple Regression Analysis*. Chapel Hill: University of North Carolina.
- Riley, Kevin. (2002). Motor Vehicles in China: the Impact of Demographic and Economic Changes. *Population and Environment* 23(5), 479-494.
- Santin, Olivia Guerra, Laure Itard, and Henk Visscher. (2009). "The Effect of Occupancy and Building Characteristics on Energy Use for Space and Water Heating in Dutch Residential Stock." *Energy and Buildings* 41(11): 1223-1232.
- Schuler, Andreas, Christoph Weber, and Ulrich Fahl. (2000). "Energy Consumption for Space Heating of West-German Household: Empirical Evidence, Scenario Projections and Policy Implications." *Energy Policy* 28(12): 877 - 894.
- Snijders, T.A.B., and Roel J. Bosker. (1999). *Multilevel Analysis: An Introduction to Basic and Advanced Multilevel Modeling*. Thousand Oaks: Sage.
- Stone, B., and M.O. Rogers. (2001). "Urban Form and Thermal Efficiency - How the Design of Cities Influences the Urban Heat Island Effect." *Journal of the American Planning Association*, 67(2): 186 - 198.
- Tommerup, H., and S. Svendsen. "Energy Savings in Danish Residential Building Stock." *Energy and Buildings* 38(6): 618-626.
- U.S. Energy Information Administration. (2010). "Residential Energy Consumption Survey (RECS)." <http://www.eia.gov/consumption/residential/index.cfm>.
- Verbeeck, Griet, and Hugo Hens. (2005). "Energy Savings in Retrofitted Dwellings: Economically Viable?" *Energy and Buildings* 37(7): 747-754.
- Wiedenhofer, Dominik, Manfred Lenzen, and Julia K Steinberger. (2012). "Spatial and Socio-economic Drivers of Direct and Indirect Household Energy Consumption in Australia." In *Urban Consumption*, ed. Peter W Newton. Collingwood, Australia: CSIRO Publishing, 251-266.

- Xie, Yanqun, Nianping Li, Shuqin Chen, Fengmei Sun, Ji Ni, and Hui Zhou. (2007). "Survey and Partial Correlation Analysis of Energy Consumption of Residential Buildings in Changsha City (Changsha Shi Juzhu Jianzhu Nenghao Diaocha ji Pianxiangguan Fenxi)." *Gas and Heat (Meiqi yu Reqi)* 5: 85 - 88.
- Xinhua. (2010) "High-Speed Rail Spearheads China's Efforts to Boost Economy: Legislator." [http://news.xinhuanet.com/english2010/china/2010-03/03/c\\_13195984.htm](http://news.xinhuanet.com/english2010/china/2010-03/03/c_13195984.htm).
- Xinhua. (2012). "Water Conservation Urged as 'Spring City' Dries." [http://news.xinhuanet.com/english/china/2012-04/09/c\\_131514998.htm](http://news.xinhuanet.com/english/china/2012-04/09/c_131514998.htm).
- Yu, Bohua, Changhe Lu, and Xinqi Zheng. "A Spatiotemporal Analysis of Urban Growth: A Case Study of Jinan Municipality, China." *Chinese Journal of Population, Resources and Environment*, 4: 48 - 53.
- Zha, Donglan, Zhou Dequn, and Zhou Peng. (2010). "Driving Forces of Residential CO<sub>2</sub> Emissions in Urban and Rural China: An Index Decomposition Analysis." *Energy Policy* 38(7): 3377-3383.
- Zhang, Jiyang. (2010) "Operational Energy Consumption and GHG Emissions in Residential Sector in Urban China: An Empirical Study in Jinan." (Master Thesis, Massachusetts Institute of Technology.)
- Zhao, H., S.G. Sun, J.M. Jiang, and J.G. Zhao. (2007). "Exploration and Study on Technology of Existing Residential Building Energy-Saving Reform." *House Science* 2: 10-13.
- Zhao, J.T., and W. Lin. (2005). "Brief Analysis on Applied Economical Efficiency of Building Energy Conservation Technology." *Energy Engineering* 3: 62-63.
- Zhou, H., Niu W.J., and Ji H. (2003). Analysis of Residential Power Consumption in Summer with Various Influence Factors. *North China Electric Power* 21(3), 12-14.
- Zhou, Nan, Michael A. McNeil, and Mark Levine. (2009). "Energy for 500 Million Homes: Drivers and Outlook for Residential Energy Consumption in China." (Research Report, Lawrence Berkeley National Laboratory).