Operational Energy Consumption and GHG Emissions in Residential Sector in Urban China: An Empirical Study in Jinan

by

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ABSTRACT

Driven by rapid urbanization and increasing household incomes, residential energy consumption in urban China has been growing steadily in the past decade, posing critical energy and greenhouse gas emission challenges. Operations represent the most energy consuming phase in the lifecycle of a residential neighborhood, accounting for 80%-90% of neighborhood lifecycle energy consumption. Although a number of research efforts have focused on operational energy consumption at the household or building scale, few attempts have been made to understand the variation in energy consumption patterns across the *neighborhood* scale in the China context.

This thesis presents research on the operational energy consumption and GHG emissions in the residential sector in Jinan, a medium-size city in eastern China. Specifically, based upon four different neighborhood typologies identified in Jinan – Superblock, Enclave, Grid, and Traditional – I examine the relationship between neighborhood form and two components of operational energy consumption: in-home and common-area. The research follows two pathways. For in-home energy consumption, I use household data collected from nine Jinan neighborhoods representing the four different typologies and apply multivariate regression techniques to examine effects on fuel choice, appliance ownership, and energy use and greenhouse gas emissions. For common area energy use, I develop a deterministic estimation framework to calculate the consumption level and share by different end uses.

The research shows that from the operational energy consumption perspective, China is gradually catching up with the industrialized countries, with per household energy consumption levels in the surveyed neighborhoods reaching approximately 1/3 of the U.S. average. After accounting for electricity generation and transmission/distribution, more than 90% of neighborhood residential energy used in Jinan comes directly or indirectly from coal, resulting in considerable GHG emissions due to coal's carbon-intensity. In-home consumption accounts for 90% of total neighborhood operational energy use; the primary influencing factors include household income and size, presence of children, home ownership, living area, and households' awareness towards saving energy. Neighborhood form, on its own, has a moderate impact, mainly through apparent effects on household energy source choice and appliance ownership.

The research suggests that the Enclave – featuring moderate compactness, high presence of mid-rise buildings, a relatively organized building layout, and diverse land uses and neighborhood functions – represents a relatively energy efficient neighborhood form in the context of urban China. The Enclave potentially limits on-site coal use, improves thermal efficiency, reduces the demand for space cooling, lowers the consumption by elevators and water pumps, and facilitates the use of solar energy. Additional options for energy conservation and GHG mitigation in urban China's residential sector include enabling flexible control of space heating and accelerating the transition from coal to cleaner energy sources.

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Table of Content

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Energy and GHG Emission Challenge in the Residential Sector of China

The rapid economic expansion of China has propelled it to becoming the largest energy-consuming country of the world, with its energy demand continuously increasing in step with the pace of economic growth. Coal remains the dominant energy source of China, accounting for more than 70% of China's primary energy consumption (EIA, 2006). The booming energy demand together with the relatively greenhouse gas (GHG)-intensive coal consumption pattern poses a serious global climate change risk. China is currently the single largest GHG emitting country in the world, and the annual CO2 emission of the country is expected to reach 11.8 billion metric tons per year by 2030, increasing at an annual growth rate of 3%. Total global GHG emissions are around 28.1 billion metric tons/year in 2005, and the emission share of China is expected to grow from 21% in 2005 to 27% in 2030. (EIA, 2008)

The industrial sector currently dominates energy consumption in China (China National Bureau of Statistics, 2007), but residential energy consumption has been on the increase, as household incomes, tastes, and lifestyles change. The total residential energy consumption in China has been growing fast for the past two decades, and, according to one estimate, it will more than double between 2000 (6.6 exajoules [EJ]) and 2010 (Zhou et.al, 2009).

Rapid urbanization is a key driving force of residential energy consumption growth in China. Analysts have long pointed out that levels of urbanization are associated with higher incomes and increased household energy use (e.g., Sathaye et al., 1989; Nadel et al., 1997). Yet, much of China's urbanization is yet to come as the nation's current urbanization rate of 48% increases to an expected 65% by 2050, as announced by Chinese Academy of Social Sciences (2007). As Zhou et al. (2009) note, urbanization leads to the increased use of commercial fuels instead of traditional biomass fuels, while the increased adoption of electronic appliances, lighting, and other "amenities" of the urban residential lifestyle further contributes to the trend of energy consumption growth. With regard to GHG emissions, the average residential annual per capita CO2 emission of Chinese households is 800kg/year, amounting to a national total of 1.01 billion metric ton/year (Tonooka et.al, 2003).

In recent years, national energy security has become a critical concern for the Chinese government while at the same time China faces growing international pressure to follow a more energy efficient development path and to control its GHG emissions. The most recent Five-year Plan (2006-2010) set an energy intensity reduction goal of 20% from the 2005 level; a 14.31% reduction has been achieved by 2009 (China Government Annual Work Report, 2009). Meanwhile, it is notable that the focus of energy policies and regulations has gradually expanded from the industrial sector to other sectors including residential, as represented by the enforcement of National Building Codes and the Appliance Efficiency Standards since 2005 (Jane, et al. 2008). Given current trends, we should expect that residential energy consumption and its GHG impacts will gain higher priority in the Chinese Government's policy agenda in the near future.

1.2 Focus of this Research

This thesis focuses on neighborhood operational energy consumption and associated greenhouse gas emissions in the residential sector of China, based on an empirical analysis of nine neighborhoods in a medium-size Chinese city. The research forms part of an ongoing project at MIT, in collaboration with Tsinghua University, sponsored by Energy Foundation China: "Making the Clean Energy City in China". The "Clean Energy City" project has the goals of understanding the energy consumption and GHG emission patterns associated with neighborhood forms in China and designing low energy residential development patterns in the urbanizing China context. Together with complimentary research on transportation energy use and embodied energy consumption, the research in this thesis will contribute to the development of a full life-cycle analysis tool under the project framework. The area of study is Jinan, the capital city of Shandong Province, China. The empirical data for the analysis come from a large scale survey, carried out by Shandong University (also supported by Energy Foundation China), covering 2,700 households in nine neighborhoods representing four neighborhood typologies. Additional information to estimate common area energy consumption comes from a structural estimation method developed by the author.

The concept of operational energy consumption is originally used in building life cycle analysis (LCA), referring to the energy consumed to maintain the operational and daily-life-supporting functions of the building. In this research, we expand and further divide the conceptual boundary. Traditional LCA analysis treats operational energy consumption as a building-level concern, to be estimated based upon assumptions about building thermal condition and appliance usage. However, such an approach cannot easily provide insights into the household-scale variations related to social, economic, and behavioral attributes. Furthermore, it neglects the energy consumed outside the buildings. To better reveal the neighborhood-scale consumption patterns and to enable the connection with household-scale research, in this research we expand the concept of operational energy consumption to the neighborhood scale, and divide it into two categories: the household in-home energy consumption and the common area energy consumption (see **Figure 1**). The former refers to the energy consumed in residents' homes, while the latter refers to the energy consumed outside the household boundary to maintain the functional operation of the buildings and neighborhood public spaces.

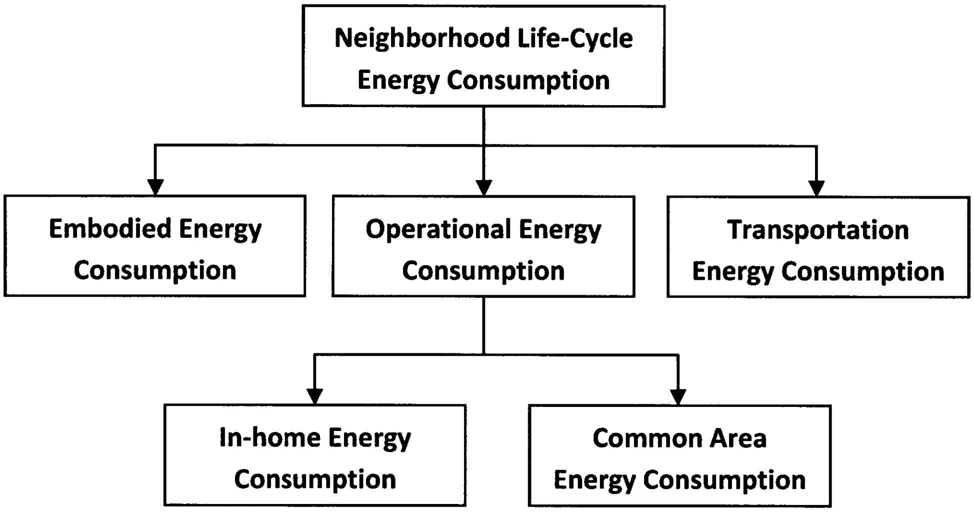


Figure 1 Components of Neighborhood Life Cycle Energy Consumption

The outcome of this research will be meaningful for policy makers and urban planners. For policy makers, we aim to improve understanding of the energy and GHG impacts associated with different residential development patterns so as to better orient energy and GHG mitigation policies under rapid urbanization. In addition, we hope to inform approaches for better guiding real estate developers towards delivering more energy and GHG-efficient neighborhood forms. For urban planners, understanding the factors – both neighborhood physical attributes and household social and economic attributes – impacting energy consumption will help to structure sustainable development at the neighborhood scale and further facilitate neighborhood planning integrating energy concerns.

1.3 Research Questions

Specifically, in this thesis I aim to answer the following research questions:

- What are the in-home energy consumption and associated GHG emission patterns of urban households in China? Does neighborhood form make a difference in determining these patterns? What other factors correlate with household in-home energy consumption and GHG emissions?
- What is the common area energy consumption and GHG emission pattern associated with different neighborhood types? What is the relative importance of in-home energy consumption and common area energy consumption in determining a neighborhood's energy consumption and GHG emission patterns, in general?
- From a policy-making perspective, what factors influencing residential energy consumption should be emphasized as policy targets? And, specifically, what neighborhood form(s) should Chinese cities promote to reduce residential energy consumption in the future?

1.4 Thesis Structure

The thesis consists of eight chapters. Chapter 2 summarizes the state of current relevant research. Chapter 3 outlines the underlying theory, the research framework and the methodology used in the analysis. Chapter 4 lays out the empirical context and describes the physical and household characteristics of the target neighborhoods. Chapter 5 presents the calculation method and the results of in-home energy consumption and GHG emissions of the nine neighborhoods. Chapter 6 analyzes the factors associated with household-level, in-home energy consumption, using regression analysis. Chapter 7 presents the estimation method and results of common area energy consumption and GHG emission patterns of the nine neighborhoods and discusses the influencing factors. Chapter 8 concludes the thesis by discussing the implications, current research limitations, and directions for future research.

Chapter 2: Literature Review

2.1 Operational Energy Consumption and GHG Emission in Life Cycle Analysis

Life cycle analysis (LCA) is a widely used tool to evaluate the environmental impact of a product. It assesses the effects of all stages – including raw material production, manufacture, distribution, use and disposal – of the product's existence (ISO, 2006). The approach has been widely applied by researchers to evaluate the energy consumption and GHG emission impact of residential buildings. A full building LCA includes three phases: construction, usage, and demolition. The usage phase can be divided into operations and maintenance. The boundary of the specific research determines the combination of phases selected in the analysis.

Essentially all research confirms that operational energy consumption is the most energy-consuming phase in a building's life cycle. Blanchard and Reppe (1998) examined the LCA energy consumption and GHG emissions of a prototype 2-story home building in Michigan and found that operational consumption accounted for 93.7% of energy consumption and 92% of CO2 emission. Wang (2007) finds similar results in the China context, by conducting LCA in four types of residential buildings in Harbin, north of China. The result shows that more than 80% of LCA energy consumption and GHG emissions can be attributed to the buildings' operational phase.

An extension of building-level LCA is its application to the residential development scale which consists of more than 1 building. A salient feature of this larger scale approach is the incorporation of transportation energy consumption into the analysis. Also, the development-scale focus enables the comparison of different residential development scenarios under the broader urban context, as buildings form developments, and developments comprise the larger urban area. Duffy (2009) provides an example, conducting LCA on residential developments belonging to four different zones of the greater Dublin (Ireland) area, and finding that the operational phase dominated both energy consumption and GHG emissions. The research also indicated that apartments consumed much less operational energy compared to detached and semi-detached residential types, since apartments have smaller size and reduced area of external envelope.

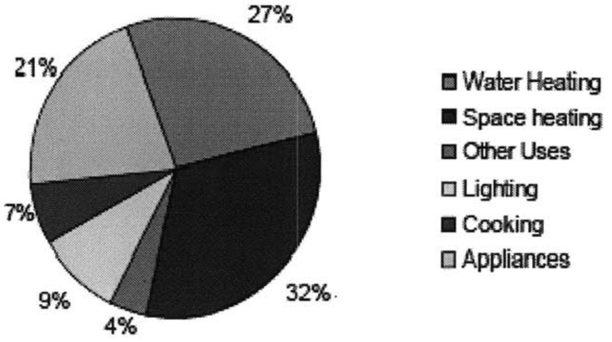
Although the results are enlightening in that they put the separate building energy consumption into a bigger picture, traditional LCA has its drawbacks. First, LCA is based more upon engineering methods; typically all household behavior-related attributes, such as intensity of appliance use, are deterministic. Second, although conducted on the neighborhood level, the total LCA is simply the sum of the separate buildings, without treating the neighborhood as a functional entity. To shed further light on these issues, the following sections offer a more in-depth review of household in-home consumption and neighborhood common area consumption.

2.2 Household In-home Energy Consumption

Overview

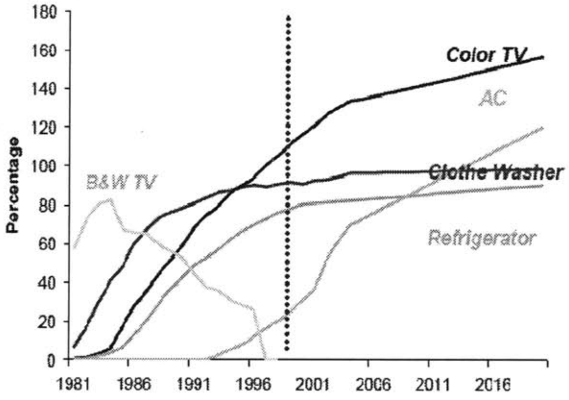
Household in-home energy consumption can be categorized by energy sources or by end uses, and a large amount of research reveals the in-home energy consumption patterns in different countries. In Unites States, electricity is the primary household energy source followed by fuel oil and natural gas; more than 50% of household energy is consumed for space heating and water heating (EIA, 2005). Wilhite et al. (1996) compared two developed countries with similar total energy consumption levels, Japan and Norway, and found that Norwegian households consumed energy dominantly for space heating and lighting, while for Japanese household water heating played a more important role. In developing countries, research has emphasized the transition from traditional energy sources (e.g., wood and coal) to modern energy sources (e.g., Alam et al. 1998). Nonetheless, the general characteristics of developing countries and their lower income levels suggest that the lack of home appliances and other consumption patterns associated with a lower standard of living have limited the dramatic growth of residential energy consumption; a dominant proportion of energy in rural and newly urbanized households is consumed for cooking (see, e.g., Tuan et al. (1996) for survey results from Vietnam, Brazil and Kenya). In general, however, energy consumption patterns vary significantly across different regions owing to the variation in climate, socio-economic conditions, dwelling types, and available energy sources.

For Chinese households, water heating and space heating dominate energy-consuming end uses, with 79% of total in-home energy directly or indirectly produced by coal (Zhou et al. 2009). From the home appliance perspective, Zhou et al. (2009) predict that the driving force of household energy consumption increases in China will be air conditioners, the ownership of which will likely rise dramatically compared to other appliances over the next 10 years (see **Figure 3**).



Source: Zhou et al. LBNL, 2009

Figure 2 End-use Energy Share in Chinese Households



Source: Zhou et al. LBNL, 2009

Figure 3 Appliance Ownership Projection for Chinese Households

Research Approaches

Two general approaches exist for researching the demand and influencing factors of in-home energy consumption: statistical and engineering. As summarized by Swan et al. (2009), the statistical approach relies on empirical household data extracted from a survey or census, and uses regression and related methods to construct models and identify the impacts of different variables. The engineering approach, on the other hand, relies on air and thermal simulation to model heating/cooling and ventilation, and the modeling process of appliance usage is highly linear, setting assumptions for all behavior related variables. In general, the statistical approach can handle both non-physical and physical variables, while the engineering approach is more capable of analyzing physical-related impacts. The following review includes research from both approaches.

Factors Affecting In-home Energy Consumption

Macro-scale: Climate and Energy Price

The climate impact on household heating and cooling has been widely studied, with day-and-night temperature and heating degree days shown to be determinant factors (Hirst et al.1986, Jones et al. 1980). The energy price is also significant. Several studies on electricity consumption conducted in EU countries (Haas, 1998, Bianco et.al, 2009) suggest consistent results of a relative low electricity price elasticity ranging from -0.06 to -0.096. The fuel price for space heating also shows a negative elasticity. As reported by Scott (1980), a 1% increase in price will result in a 0.4% decrease in heating fuel consumption.

Household Socio-Demographics

Household socio-demographics have been found to be the most influencing category on in-home energy consumption, since it influences the household's utility function and the budget constraint. Furthermore, it exerts indirect influence on energy consumption through the appliance choice, ownership and household behavior. Among the commonly tested variables, household income and household size are the two most widely shown to be significant (eg. Assimakopoulos 1992, Schuler 2000, Pachauri 2004). The respondent age also shows positive correlation with energy consumption for space heating, as indicated by Nesbakken (2001) and Liao et.al (2002). Leth-Petersen et.al (2001) found that home ownership matters in apartment blocks; in particular, rented dwellings result in more energy consumption than owner-occupied units if the heating bill is included in rent. A number of survey-based studies have been conducted in the China context. Xie et.al (2007), for example, examined the in-home energy consumption in Changsha City though a survey of 70 households and found significant effects of household income and size. A similar result is indicated by Sun et.al (2009), who analyzed the energy consumption patterns of Shanghai households through a 300-household survey.

Occupant Behavior

Occupant behavior accounts for some variation in household energy consumption not explained by socio-demographics, even though socio-demographics may to a large extent affect occupant behavior. At least three different relevant behavioral variables exist. The most obvious variable is occupant presence at home. Santin et al. (2009) found that households with residents at home during the day consume significantly more space heating energy compared to others. The second variable is indoor temperature preference, which is reflected in the temperature setting of heating equipments and air-conditioners. Hass et.al (1998) examined the impact of household in-door temperature preferences through meter-reading and a survey questionnaire, and find that a higher indoor temperature preference is associated with higher heating energy demand. Linden et.al (2006) examine energy use behavior of 600 Swedish households, and found that 51% of respondents who lowered the indoor temperature at night did it for comfort, compared to only 27% for saving energy or money. The third relevant variable is energy saving behavior. For example, Ouyang et al. (2007) conducted a survey of 100 households in Hangzhou, China and examined the impact of 8 types of household energy saving activities, including reducing usage time of ACs, setting higher temperature during summer, choosing energy efficient appliances to replace old ones, and so forth. Their results suggest a moderate impact of energy saving consciousness on household energy consumption. Feng et al. (2010) researched the pattern of energy efficient appliance purchasing in 600 households in Liaoning, China, and concluded that price and information barriers hampered energy saving equipment purchases, despite potentially important impacts on energy savings. About 55% of surveyed households reported the intention to save energy, but the actual ownership of energy efficient light bulbs and labeled appliances was still low. According to the authors, the major barriers are high initial investment costs, ignorance or distrust of the benefits of energy efficient appliances, and lack of knowledge about energy saving approaches.

Attitudes

Related to the previous point, individual attitudes, values and intentions may also influence energy consumption. More rigorously, attitudes and intentions shape behaviors which influence energy use. For example, an individual with particular attitudes about or preferences for "protecting the environment" may exhibit different behaviors in terms of energy consuming activities. The role of attitudes in determining behaviors has received extensive theoretical and empirical treatment in the field of psychology; and analyses suggest that attitudes and norms do measurably influence intentions and behaviors (e.g., Armitage and Conner, 2001). Nonetheless in the area of household energy consumption, the empirical evidence remains a bit ambiguous. Vringer et.al (2007) examined the value patterns, problem perceptions and motivations with regard to climate change and energy use through a 2304 sample household survey in the Netherlands. They find that families "least motivated to save energy" consume 4% more energy, but otherwise find no significant difference between the energy requirements of households with different value patterns after controlling for socio-demographic variables. Wokje et.al (2009) examined the psychological patterns related to household energy use and savings through a 189-sample survey in Dutch households. The results also indicate that energy use is primarily determined by socio-demographics, and psychological variables only have limited impact on energy savings.

Appliances

Household appliance ownership and usage directly determine the energy consumption pattern of the household. However, these two categories of variables are also highly dependent on household socio-demographics, preferences, behavior and attitudes. Incorporating the appliance ownership and usage variables into the regression model will dilute the explanatory power of other variables. Thus in many studies accounting for a wide range of variable categories, appliance ownership and usage are not included as input variables. Some studies use a simplified index to summarize the power and usage of appliances (Fuks, 2008), or use the total number of main appliances as input variable (Ouyang, 2007). Unsurprisingly, the impact of these variables on in-home energy consumption is significant.

As Dubin and McFadden (1984) formalize theoretically and examine empirically, households' choice of home appliance ownership and subsequent appliance use actually represent two interrelated decisions. The appliance ownership decision is a typical discrete choice, since households choose among a limited number of a certain appliances to own. The second process however, is a continuous choice of how much to actually use the appliance – a continuous variable. The two processes are interrelated in that the utilization choice is conditional on the ownership choice, but ownership choice may also be conditional on expected utilization levels. This reality poses particular econometric challenges, as discussed in detail in the methodology section. Vaage (2000) used the binominal logit regression to model the discrete choice of heating appliance ownership in Norwegian households, and used the linear regression to model the continuous conditional energy demand. This methodology is also used by other researchers such as Nesbakken (2001).

Home and Building Physical Attributes

The home and building physical attributes primarily affect space heating and cooling energy consumption, and lighting to some extent. For research work using statistical methods as the analytic approach, the commonly examined home physical attributes include the following categories (Santin et al. 2009):

- Vintage of Building
- Type of Dwelling: single detached, double, row, flat, etc.
- Design of Dwelling: useful living area, orientation, window-to-wall ratio, roof type, presence of garage, shed, basement, etc.
- Insulation: ground, window, and roof insulation
- Heating System: technology, thermal control and efficiency
- Energy Type

Using variables defined from these categories, Santin et al. (2009) conducted stepwise regression analysis using a survey-based dataset of 15,000 houses in Netherlands. The results indicate that physical attributes alone explain 41.7% of the variation in household energy consumption, with an extra of 4.2% explained by household characteristics and behavior. All home physical variables in the model are significant except the roof insulation. The strong impact of home physical attributes is also supported Tonn et al. (1988). In their regression models based on data from 100 sub-metered homes, the home physical attributes played a significant role, with total model R^2 values ranging from 0.80-0.91.

In China however, the impact of physical attributes becomes vague from an empirical perspective. According to the partial correlation results produced by Xie et al. (2007), none of building height, household floor and home orientation is significantly correlated with household in-home energy consumption in apartment buildings in Changsha. Chen et al. (2009) and Sun et al. (2009) examined household energy consumption in Shanghai using a similar regression method, and found that building age, home orientation and building shade had no significant correlation with household energy consumption after controlling for other socio-demographic and behavioral variables.

Compared to the statistical approach, the engineering approach directly measures the relationship between building physical attributes and energy consumption, relying on building simulation tools. The work of Depecker et al (2001) is highly representative of this research style. Through geometric simplification and computer modeling, they examined the relationship between building shape coefficient and heating energy consumption, and found that under rigorous climate condition the most energy-efficient shape consumes nearly 50% less than the least energy efficient one. An abundance of research focuses on building-level physical attributes like this. But since the focus of this research is on the neighborhood scale, the review will not cover more building-scale research.

2.3 Common Area Energy Consumption

Common area energy consumption has long been neglected by researchers. Two reasons account for this ignorance. First, the residential sector in US is dominated by detached, semi-detached or row houses, for which common area consumption is basically irrelevant. According to a US housing survey (HUD and US Census Bureau, 2007), single-family houses account for nearly 70% of the nation's total housing stock. For these housing units, all in-building space is owned by the homeowner and the "common area" is rare. Second, although some building energy simulation tools take into account common area energy consumption such as elevator and corridor lighting, they treat the building as an entity and there is no separation between in-home consumption, which is under control of households, and common-area consumption, which is beyond the control of households.

Although there is little research focusing on common area energy consumption, some insights can be found from research on related elements such as elevators and water pumps. Sachs (2005) reviewed a number of building simulation results and concluded that the energy use of elevators is often treated as unpredicted, and the simulation results can vary significantly. According to Al-sharif (2004), elevators typically use 3%-5% of the electricity in modern buildings. Enermoal (2004) further elaborated that the energy consumption of elevators can vary from 1,900KWH/year for a lightly loaded low-rise hydraulic elevator to 15,000KWH/year for a heavily loaded elevator in a high-rise commercial building. Cheng (2002) examined the energy consumption share of different water-use related components in a six-story residential building in Taibei, and found that the pump energy consumption is very limited compared to that of water heaters and water boilers (2.7% v.s. 82.4% and 14.9%). While general research on lighting energy use is abundant, most research focuses on household in-home lighting energy efficiency. Little representative research work examines purely common area lighting. In general, current research on common area energy consumption is highly piecemeal, with little evidence of work to integrate these separate elements.

2.4 City-Scale Urban Form Impact

Another research perspective of residential energy consumption and GHG emission is on the city scale. Although transportation tends to be the primary focus on this research scale, the impact of high and low density development on operational energy consumption has also been emphasized. For example, Norman et al. (2006) conducted LCA on two residential settlements of different density in Toronto, and found that the high density case consumed less than half of operational energy and produced half the GHG emissions compared to the low density case. Ewing et al. (2008) emphasized the relationship between urban form and people's housing choice in the US, and found that households in sprawling regions are more likely to live in large-size single houses thus consume more operational energy than those in compact regions. Stone et al. (2001) examined the impact of residential density on urban heat island formation in Atlanta, and found that low density development contributed more radiant heat energy to surface heat island formation than high density development. In general, most city-scale research reaches a similar conclusion that high-density compact residential development is more favorable with regard to energy saving and GHG reduction.

2.5 Energy Sources and GHG Emission

The last but not least concern is the intensity of GHG emission associated with different energy sources. To produce the same amount of utilizable energy, the amount of GHG emission varies by energy sources. According to the US EPA (2010), the CO2 emissions associated with producing one million BTU of is 92.9 kg for coal, compared to 70.9 kg for gasoline, and 53.1 kg for natural gas. In the China context, researchers have observed the improvement in energy productivity and the evolution of the energy structure, represented by reduced energy consumption per GDP and reduced reliance on coal (Crompton et al. 2004, Fisher-Vaden et al. 2006). But, a widely accepted consensus is that coal will still dominate China's energy sector over the 20-year horizon, and the substitution by gas and nuclear will only take place at a moderate speed (Vuuren et al. 2003).

2.6 Summary and Significance of Research

Current research on operational energy consumption primarily focuses on in-home energy consumption, while the common area energy consumption is often neglected. Given this limitation, no attempt has been made to integrate in-home consumption and common area consumption at the neighborhood level of analysis. Statistical analysis based on large-scale surveys and national census databases has been widely conducted in other countries, but due to budget limitations and information barriers, very few large scale surveys have been done in this area in China, with most surveys covering less than 300 observations thus limiting cross-neighborhood comparison possibilities. Moreover, the implication of "compact" residential development remains vague for China, where the residential sector already consists of mainly multi-story buildings with high densities.

The research in this thesis thus represents innovative work in the China context for at least the following reasons:

1) The availability of a 2300+ household survey covering 9 neighborhoods and enabling comparison of in-home consumption and GHG emission pattern across different neighborhood types;
2) The development of a systemic framework to estimate neighborhood common area energy consumption under data limitations; and
3) An analysis incorporating both in-home and common area energy consumption to produce a "big picture" view of neighborhood energy consumption, its relevant relative dimensions and contributing factors.

Chapter 3: Theory, Framework and Methodology

3.1 Theory

Consumer Theory

The most fundamental theory underlying household in-home energy consumption is microeconomic consumer theory, which formalizes the relationship between personal preferences, consumption, utility, and demand. According to this theory, utility realization is the final objective of all consumer-related activities. Fundamentally, energy is one option among consumers' various choices that can lead to increased utility; energy consumption itself does not provide utility, rather we use energy (say, gas) as an "intermediate" good towards the final consumption of another good (say, cooked food). In other words, households purchase energy as an intermediate means towards utility, rather than for energy itself. A simplified household utility function can be expressed as:

(1) $U = f\ (E,\ C_1, C_{2\,,} C_3, \ldots)$

Where U is the household utility, E is the energy consumption, C_i is the amount of consumables (Note: not durables) other than energy, such as food and clothes. The total utility U is jointly determined by the consumption share of different consumables.

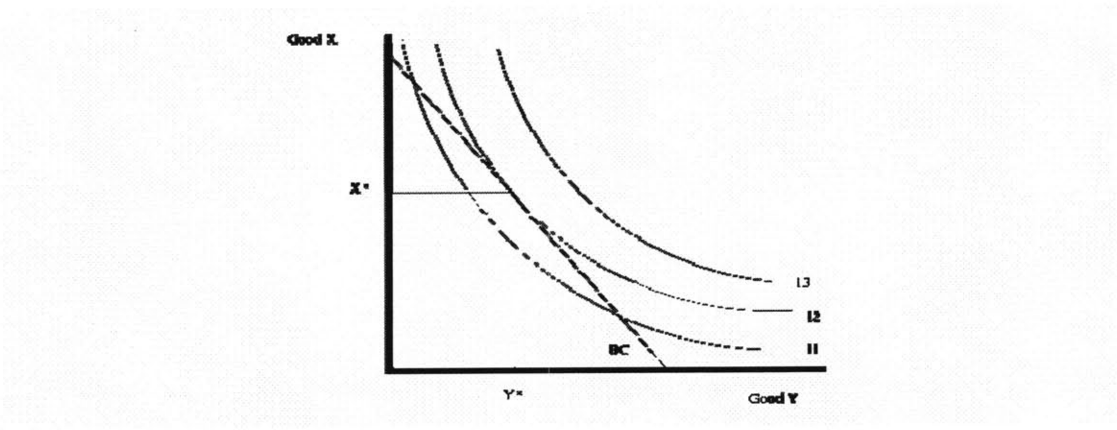
However, unlike food and clothes, energy is not consumed directly, and its consumption relies on the household appliances as intermediates to achieve different purposes such as convenience, entertainment, and comfort. Thus the ownership and usage of appliances enter the utility function in the following way:

(2) $E = f_e\ (A_1, I_{1,} A_2, I_2, A_3, I_3 \ldots)$

Where A_i is the ownership of different appliances and I_i is the usage intensity of each appliance. Energy consumption, E, is jointly determined by the type and number of appliances owned by the household and how these appliances are utilized.

Utility Maximization

The fundamental assumption of consumer theory is that consumers are rational decision makers who seek to maximize utility (Silberberg & Suen, 2001), subject to a budget constraint. The choice process is conceptualized through indifference curve analysis (Mankiw, 2005) (See **Figure 4**). Assume that the consumer only consumes two types of goods, then all consumption bundles on the same indifference curve, such as Curve I1, will generate the same level of utility. The consumer's bundle choice cannot exceed the budget constraint (line BC). Utility is maximized when and only when the budget constraint curve is tangent to the indifference curve.



Source: Principles of Economics, Mankiw, 2005

Figure 4 Indifference Curve and Budge Constraint

The actual situation becomes more complex when more choices of goods are introduced, but the fundamental rationale remains unchanged. Recall from functions (1) and (2), the budget of a household in a given period can be expressed as follows:

(3) $M = M_c + M_a$

(4) $M_c = P_e * E + P_{c1} * C_1 + P_{c2} * C_2 + P_{c3} * C_3 \dots$

(5) $M_a = P_{a1} * \Delta A_1 + P_{a2} * \Delta A_2 + P_{a3} * \Delta A_3 \dots$

Where M_c is the budget spent on consumables and M_a is the budget spent on appliances (durables). P_e is the energy price, and P_{ci} is the price of other consumables. P_{ai} is the price of different appliances (durables), and ΔA_i is the increment of appliance i during this period. ΔA_i will result in change of A_i in Function (2).

Tragedy of the Commons

The last theoretical perspective relevant to this thesis is related with neighborhood common area energy consumption. We can consider this a case of the tragedy of the Commons, as initially raised by Hardin (1968). This refers to a situation in which multiple individuals, each acting independently, and solely and rationally consulting their own self-interest, will deviate from the optimized use of resource even when it is clear that it is not in anyone's long-term interest for this to happen. In a neighborhood, the in-home energy consumption is purely under control of individual households, but the common area energy consumption is determined by the joint usage of all households. The conceptual function of utility and budget is shown below:

(6) $U_E = U_{HH} + U_{COM}$

(7) $M_E = M_{HH} + M_{COM}$

Where U_E is the household total utility derived from energy consumption, U_{HH} is the utility derived from in-home consumption and U_{COM} is the utility derived from common area consumption. M_E is the household total energy budget, M_{HH} is in-home energy bill and M_{COM} is common area energy bill.

Since the common area energy bill is paid collectively by residents on a fixed, per square meter home area basis, the behavior change of an individual will not directly affect his common area energy bill. Without a cost-saving incentive, households are indifferent about energy saving in common area, thus are more likely to consume energy in an uncontrolled manner even though U_{COM} does not increase. The thriftless consumption of all residents will increase M_{COM}, and further decrease M_{HH} given a fixed budget, M_E. The decrease in M_{HH} will simultaneously reduce U_{HH}, and finally reduce U_E.

3.2 The Conceptual Framework

Figure 5 shows the conceptual framework, illustrating how the household characteristics and neighborhood characteristics jointly affect residential energy consumption through the utility maximization behavior of households. All the choices presented in the diagram, including the energy source choice, the appliance ownership choice and usage choice, are derived demands upon the ultimate demand of higher utility. Unless specified, the solid lines indicate "constrain" or "determine", while the dashed lines indicate "affect".

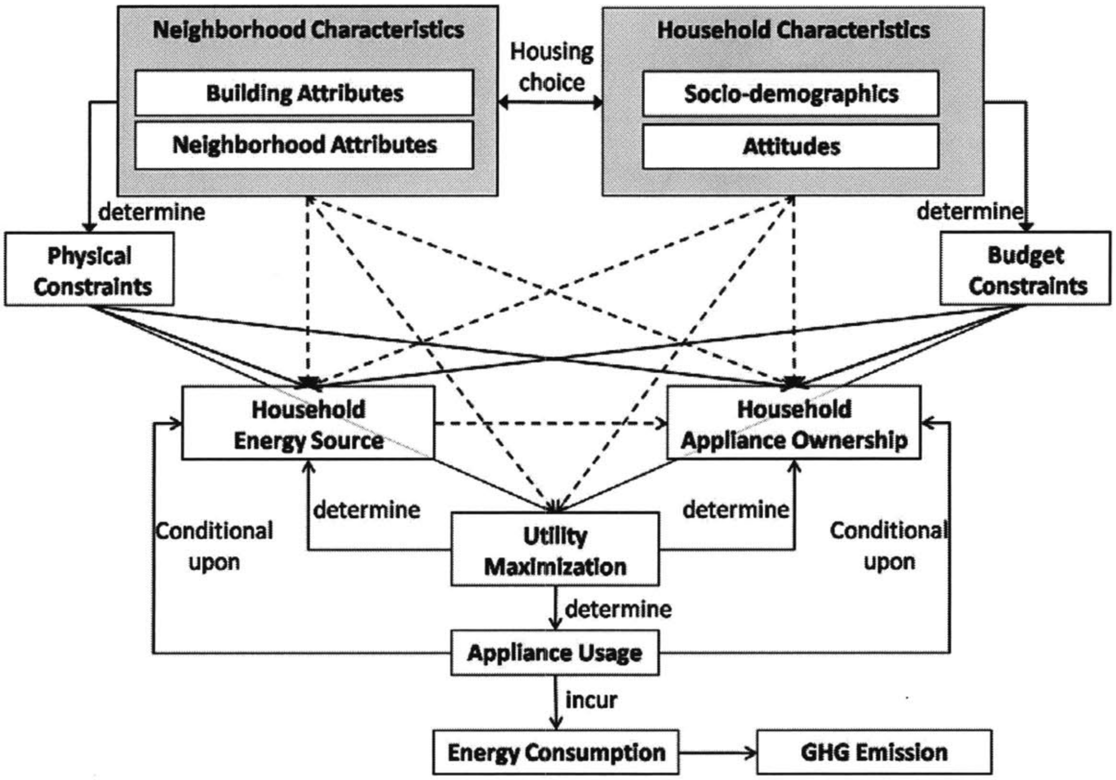


Figure 5 The Conceptual Framework

3.3 Methodology

Considering the data limitations, I follow two pathways. For in-home energy consumption, I apply statistical models to empirical data collected through a survey. For common area energy consumption, due to the lack of empirical data available, I establish an estimation framework to determine the scale of common area energy consumption. Comparative analysis and multivariate analysis are the two major methods applied in this research.

The Survey Approach

The empirical data come from a large-scale household survey conducted in the summer of 2009 in Jinan[1]. Nine neighborhoods of four different representative urban form typologies were selected (the following chapter provides a detailed description of the typologies). Shandong University carried out the survey, aiming to select 300 households from each of the nine neighborhoods using simple random sampling, without replacement. Eligible respondents were adults, aged 20 to 65 years, who resided in private dwellings (either rental or owner occupied). In households with more than one potentially eligible participant, the individual with the most recent birthday was asked to complete the study questionnaire. A sample questionnaire is attached in the Appendix. A total of 2700 eligible participants filled the questionnaire. Shandong University also conducted the data entry and initial data clean-up.

Notably, the survey questionnaire contains two sections, one for transportation activities (trips, modes, distances, etc.) from which transportation energy consumption could be estimated and one for in-home energy consumption. The content related to in-home energy consumption includes the following categories:

1) Household socioeconomics and demographics, including household size, household income, children and elderly, and home ownership status.
2) Home physical attributes, including home constructed area, building height, and whether the household lives on top floor of the building.
3) Appliance ownership, including AC, refrigerator, TV, desktop, and solar water heater

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[1] The household survey data were kindly provided to the author by Prof. Ruhua Zhang, at Shandong University, from a study carried out under a contract with the Energy Foundation-China.

ownership.

4) Energy source and energy bill, including monthly average electricity bill, gas bill, and annual coal bill.
5) Attitudes, including attitudes towards saving energy and preferences for a "prestigious" life style.

Linear Estimation

Since we obtained no empirical data for neighborhood common area energy consumption, we develop a linear, deterministic estimation framework, utilizing neighborhood-level data such as household count and road density, a neighborhood sketch-up 3D model, and engineering parameters. The in-building common area consumption includes lighting, elevator, water pump and access security. The out-of-building common area consumption includes lighting and underground parking. The underlying assumptions and parameters are established based on local planning guidelines and regulations, architectural and engineering manuals, and other literature. The methodology is further explained in Chapter 7.

Comparative Analysis

The study uses comparative analysis to examine the energy consumption and GHG emission patterns of different neighborhoods, as well as the energy structure and per household, per capita, and per square meter energy intensity. The share of in-home and common area energy consumption will also be examined to determine the relative importance of each.

Multivariate Analysis

Based on the survey data, I conduct multivariate analysis to test hypotheses regarding the factors affecting in-home energy consumption and GHG emission. I also use the logistic models to examine the household energy choice and appliance ownership choice. Considering the endogeneity problem, we try the two-stage modeling approach. The three major modeling approaches are introduced below.

➢ Linear Regression Model

The linear regression approach is to regress the log-transformed household energy consumption or GHG emissions on a set of variable vectors, based on the conceptual framework outlined in **Figure 5**. The model takes the following form:

(8) $$\mathrm{Ln(E)} = \beta_{E1}H + \beta_{E2}A + \beta_{E3}B + \beta_{E4}ES + \beta_{E5}AO + \beta_{E6}N + \delta$$

(9) $$\mathrm{Ln(G)} = \beta_{G1}H + \beta_{G2}A + \beta_{G3}B + \beta_{G4}ES + \beta_{G5}AO + \beta_{G6}N + \delta$$

- H is a vector of household socio-demographics
- A is a vector of household attitudes
- B is a vector of home physical attributes
- ES is a vector of energy sources and usage
- AO is a vector of appliance ownership
- N is a vector of neighborhood physical attributes
- δ is the error term

The model is applied to household total energy consumption, as well as to the energy consumption of individual energy sources and associated GHG emissions. For each model, only the relevant variables are included.

➢ Logistic Regression Model

The logistic model takes the following basic form:

(10)

$$Pr(C = 1) = \frac{exp\ (\beta_1 H + \beta_2 A + \beta_3 B + \beta_4 ES + \beta_5 N + \delta)}{1 + exp\ (\beta_1 H + \beta_2 A + \beta_3 B + \beta_4 ES + \beta_5 N + \delta)}$$

- $Pr(C = 1)$ is the probability that a household uses certain energy source or owns certain appliance.
- H is a vector of household socio-demographics,
- A is a vector of household attitudes,
- B is a vector of home physical attributes,
- ES is a vector of energy sources and usage,
- N is a vector of neighborhood physical attributes,
- δ is the error term.

The model is applied to household choice of energy sources, and household appliance ownership. For each model, only the relevant variables are included.

- **The 2-Stage Approach**

For households, energy is consumed through the use of appliances. The use of appliances is conditional upon a given set of appliance ownership, which is included in the energy consumption model in the form of variable vector AO in Equation (8). However, the demand for appliances and their use are related decisions by the consumer, meaning that in theory the appliance ownership should not be treated as exogenous. In the modeling process, this endogeneity problem would arise as a result of omitted variables. For example, the indoor temperature preference (P) affects household energy consumption pattern through HVAC activities. In this case, the true linear model should take the following form:

$$(11)\ \mathrm{Ln(E)} = \beta_{E0} + \beta_{E1}H + \beta_{E2}A + \beta_{E3}B + \beta_{E4}ES + \beta_{E5}AO + \beta_{E6}N + \beta_{E7}P + \mu$$

However, the vector of temperature preference is omitted in Equation (8) due to data limitation. So the preference variables will be absorbed by the error term, and we actually estimate:

$$(12)\ \mathrm{Ln(E)} = \beta_{E0} + \beta_{E1}H + \beta_{E2}A + \beta_{E3}B + \beta_{E4}ES + \beta_{E5}AO + \beta_{E6}N + \delta$$

Where $\delta = \beta_{E7}P + \mu$

But we also know that correlation exists between P (temperature preference) and AO (appliance ownership). Now in Equation (12) the variable vector AO is correlated with the error term, violating the underlying assumption of OLS regression.

To deal with this endogeneity problem, the two-stage approach is introduced. In the first stage, the probability of household appliance ownership is estimated through the logistic regression model (see Equation (10)). Notably, the logit model should include at least one instrumental variable which influences appliance ownership but is not correlated with the error term in Equation (12).

The estimated appliance ownership variable is given by:

(13)

$$P\_AO = Pr(C = 1 | \mathrm{I}^* \in \mathrm{H, A, B, ES, N}) = \frac{exp\ (\beta_0 + \beta_1 H + \beta_2 A + \beta_3 B + \beta_4 ES + \beta_5 N)}{1 + exp\ (\beta_0 + \beta_1 H + \beta_2 A + \beta_3 B + \beta_4 ES + \beta_5 N)}$$

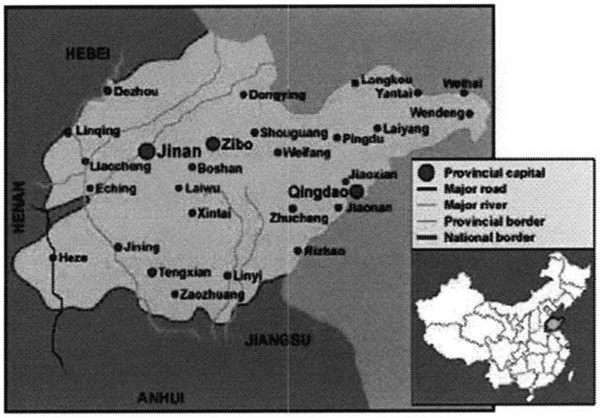
Where I^* stands for the instrumental variable(s).

In the second stage, the estimated appliance ownership P_AO is used to replace the observed ownership AO in Equation (12). Since P_AO is not correlated with omitted variables, it is no longer correlated with the error term, and the endogeneity problem is addressed. However, it is notable that the feasibility of the two-stage approach strongly depends on the quality of the instrumental variables. If the instrumental models are weak, the model may perform poorly.

Chapter 4: Empirical Context--Jinan, China

4.1 Jinan Overview

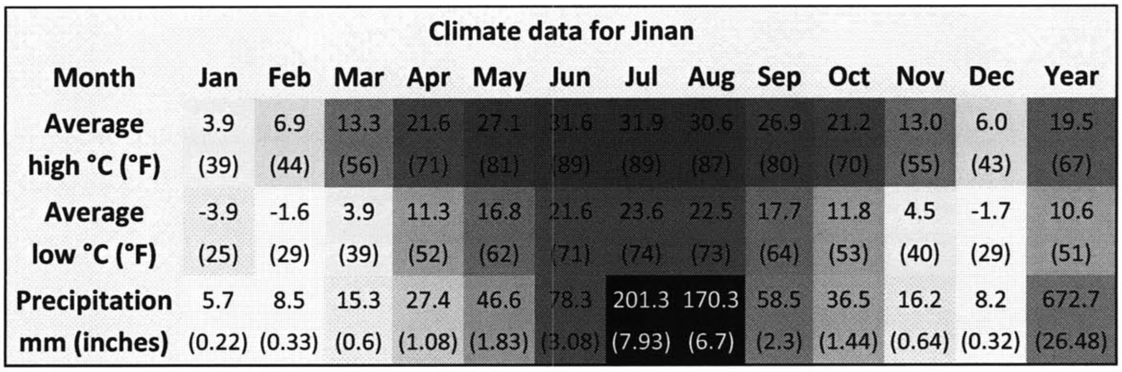
Jinan is the capital of Shandong Province, China, famous for its culture and history of more than 3000 years. *"Located in the north-western part of Shandong, the city occupies a transition zone between the northern foothills of the Taishan Massif to the south of the city and the valley of the Yellow River to the north"* (Wikipedia, 2003). The GDP of the city is 301.7 billion RMB in total (44 billion USD) and 46,000 RMB per capita (6,700 USD), and the total population is 6.6 million, among which 3.4 million are registered urban population(China National Bureau of Statistics, 2009).



Source: Asia Times, 2005

Figure 6 Location of Jinan, Shandong Province

Jinan has a humid subtropical climate with four well-defined seasons (see **Table 1**). The summer is hot and rainy, with the average high temperature reaching 85°F through June to August. The winter is cold and dry, although it is slightly less harsh compared with other cities in the North of China, owing to the city's proximity to the Bo Sea.



Climate data for Jinan

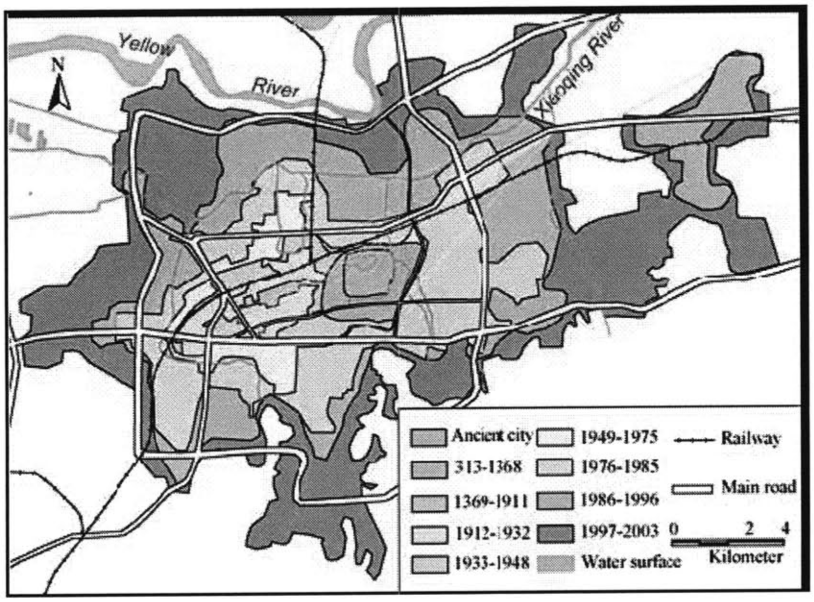
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C (°F)	3.9 (39)	6.9 (44)	13.3 (56)	21.6 (71)	27.1 (81)	31.6 (89)	31.9 (89)	30.6 (87)	26.9 (80)	21.2 (70)	13.0 (55)	6.0 (43)	19.5 (67)
Average low °C (°F)	-3.9 (25)	-1.6 (29)	3.9 (39)	11.3 (52)	16.8 (62)	21.6 (71)	23.6 (74)	22.5 (73)	17.7 (64)	11.8 (53)	4.5 (40)	-1.7 (29)	10.6 (51)
Precipitation mm (inches)	5.7 (0.22)	8.5 (0.33)	15.3 (0.6)	27.4 (1.08)	46.6 (1.83)	78.3 (3.08)	201.3 (7.93)	170.3 (6.7)	58.5 (2.3)	36.5 (1.44)	16.2 (0.64)	8.2 (0.32)	672.7 (26.48)

Sunshine hours	170.9	172.4	212.8	242.9	275.2	258.2	214.5	219.0	221.1	215.1	177.1	167.6	2,546.8
% Humidity	53	50	47	46	50	55	72	75	64	58	56	55	57

Source: China National Meteorological Center, 2007

Table 1 Climate Data of Jinan

Jinan is urbanizing rapidly. Although the speed of population growth in Jinan has been decreasing since the mid 1980s, the pace of urbanization has been accelerating, especially after the economic reforms in 1978. The rate of urban expansion was around 55 ha/year between 1976 and-1996, and substantially increased to 232 ha/year during 1997-2003. In 2003, the built-up area of Jinan city reached 24,163 ha, 6 times higher than that in 1975 (Yu, et al. 2006), as shown in Figure 7.



Source: Yu et al. 2006

Figure 7 Urban Area Expansion of Jinan

4.2 Energy Sources in the Residential Sector of Jinan

The residential sector in Jinan consumes four types of energy: electricity, gas, coal, and municipal centralized heating, as discussed below.

Electricity

The electricity coverage of Jinan urban area reached 100% in the 1990s. Jinan Electricity Supply Company (JESC), a state-owned enterprise, is the city's only electricity provider, offering identical electricity price for residential users city-wide. Residential electricity consumption in Jinan peaks during the summer season due to cooling loads, but in recent years the winter consumption has increased significantly, reflecting the trend towards increased household ownership of electric heating appliances as a complement (or substitute) to traditional heating approaches (JESC, 2010).

With regard to both electricity generation (287,000 GWH) and installed generating capacity (61 million KW), Shandong Province ranks second among all provinces in China. Coal is the dominant energy source for electricity generation in Shandong - 99% of electricity is generated by coal power plants (JESC, 2010).

Gas

Gas in Jinan is mainly consumed for cooking, water heating and a very limited proportion of space heating. Three types of gas, namely natural gas, liquefied petroleum gas and coal gas, are consumed in the residential sector, covering 97.8% of urban households (Jinan Government Annual Work Report, 2010). Residential neighborhoods constructed after 1995 normally have gas pipelines installed, through which either natural gas or coal gas can be directly transferred to households. Steel-bottled liquefied petroleum gas is available for households which cannot access piped gas.

Coal

Coal has been used in Jinan's urban households for decades, serving space heating, water heating and cooking purposes, but its use is fading rapidly due to the expansion of gas and centralized heating coverage, which offer increased safety, convenience, and cleanliness. New residential neighborhoods in Jinan normally have access to municipal centralized heating, so coal is only consumed in older neighborhoods and the "urban villages", which have been enfolded into the city through rapid urbanization. Coal for household use takes the form of honeycomb briquettes, the purity, heat value and smoke impact of which vary according to the quality. Households use coal stoves with chimneys to burn coal for space heating. For cooking purpose, small movable stoves are also used.

Centralized Heating

The household centralized heating coverage in Jinan has reached 49% (Jinan Government Annual Work Report 2010), and the renewal of old residential neighborhoods to install centralized heating pipelines has been taking place city wide. Centralized heating delivery takes the form of hot water or steam, with coal as the primary energy source for generation. The centralized heating system does not meter individual household heating consumption; instead, the heating fee is calculated based on the constructed area of the home. Households cannot adjust the in-home temperature. The heating period lasts from Nov. 5 to March 15, 140 days in total.

4.3 The Neighborhood Typologies in Jinan

As part of the "Clean Energy City in China" project, MIT and its local partners identified five neighborhood typologies, representing distinct neighborhood forms, related in part to China's city development history: "Traditional", "Grid", "Mixed Enclaves", "Superblock" and "Villa". **Table 2** provides a summary of the typology characteristics as well as the particular neighborhood cases chosen to represent the typologies (and serving as the sampling frame; with the exception of the "Villa" typology which is not covered in the empirical study).

Typology	*Characteristics*	*Cases*
Traditional	2-3 story courtyards; fractal /dendritic fabric off a main shopping street, on-site employment; not gated	Zhang Village
Grid	Block structure with different building forms contained within each block, retail on connecting streets; not gated	Old commercial district
Mixed Enclave	Linear mid-rise walk-ups; housing integrated with communal facilities (kindergartens, clinic, restaurants, convenience shops, sports facilities, etc); gated or partially gated	Wuyingtan Dongcang Foshanyuan Yanzishan
Superblocks	High-rise slabs and towers in park with homogeneous residential use; gated	Lv-Jing Sunshine 100 Shanghai Garden
Villa	Townhouses, single houses with homogeneous residential use; gated	N/A

Table 2 Neighborhood Typology and Cases

Traditional

The Traditional neighborhoods have the longest history in Jinan, dating back to at least the early 1900s. Low-rise brick-structure courtyard with 2-3 floors is the dominant building type, but the number of mid-rise buildings with 4-6 floors has been increasing. A large number of Traditional neighborhoods are "urban villages," engulfed in the ongoing process of urbanization. While traditionally agricultural, the residents no longer work in this sector. Instead, they take relatively low-income jobs in the service sector or work in small businesses. With growing migrant flows from rural areas to Jinan, the Traditional neighborhoods also serve as a cheap source of rental housing for migrant workers.

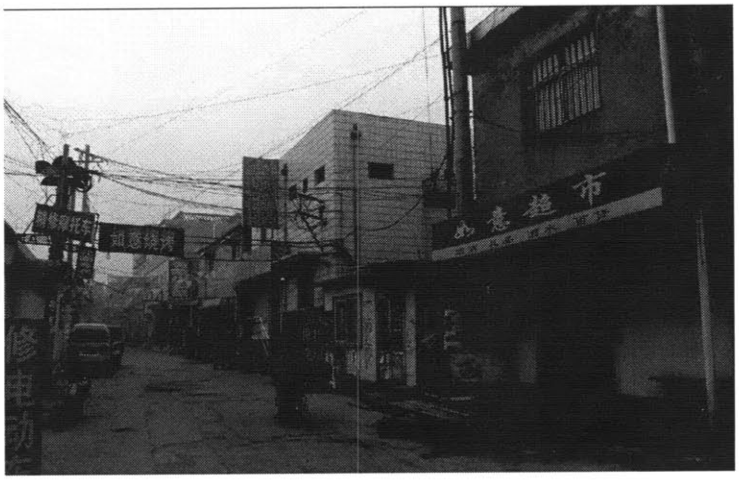


Figure 8 Zhang Village-Traditional

Grid

The Grid represents a typical combination of residential land uses mixed with commercial land use. The Grid neighborhoods are not gated, with direct access to urban public streets with commercial activities. The building types and building ages in the Grid are highly diverse since the construction phases of different clusters in the Grid are independent. Residents in Grid are also diverse, with heterogeneous socio-demographic characteristics.

Figure 9 Old Commercial District-Grid

Mixed Enclave

The Mixed Enclave typology derives from the state-enterprise residential compound ("Danwei Dayuan"), which dominated the urban residential sector of China for nearly 30 years from 1950 to 1980. The core concept of the residential compound is work-residence proximity, with fully integrated neighborhood service functions including commercial, educational, medical and entertainment. Residents of a compound normally belonged to the same employer such as a state-owned enterprise or a governmental sector, and the homeownership was granted through the welfare housing distribution system before the housing reforms took place. Beyond the residential compounds, other Enclaves continued to be developed in Jinan in the 1980s as the outcome of a national residential development experiment aiming at promoting convenient neighborhood life through integrated service functions (Lue, et al. 2001). But after the housing reform, this typology has given way to the Superblocks.

Figure 10 Yanzishan-Enclave

Superblock

The Superblocks are the dominant real estate development products of contemporary China. Matching up with the housing reform in 1998 when the welfare housing distribution policy was terminated, nearly all the residential developments in Jinan after 2000 take the form of the Superblock. The majority of Superblocks are developed by for-profit real estate companies. These so called "commercial residential housing" are sold at full market price thus lower income groups are filtered out. The land use in Superblocks is homogeneously residential, with limited small retails serving residents' daily needs. High-rise and super high-rise buildings are prevalent given the profit-driven incentive to make full use of the land.

Figure 11 Sunshine100-Superblock

4.4 Summary of Neighborhood Physical Attributes

Figure 12 shows the spatial location of the nine neighborhoods in Jinan representing the typologies described above. Among them, four are closer to the inner city, while the other five are further out.

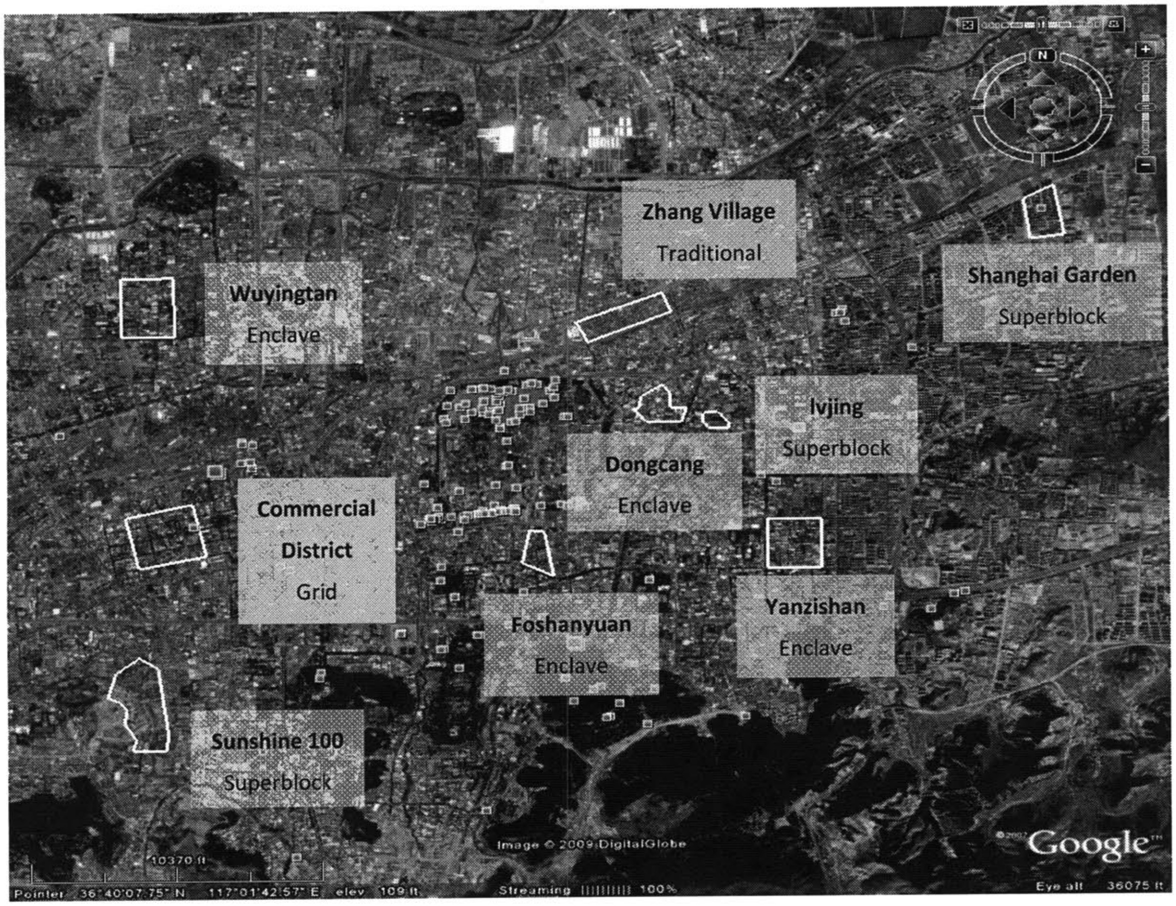


Figure 12 Spatial Location of the Survey Neighborhoods

Table 3 summarizes the building attributes of the nine neighborhoods. In general, low-rise slab (6-9 stories) is the most common building type, but the Superblocks have a higher presence of high-rise buildings. Building age is also more homogeneous in the Superblocks. Yanzishan (one of the Enclaves) and the Grid have more diverse buildings with regard to both building height and building age. Masonry-concrete is the most common building structure, while steel-concrete plays a more important role in Superblocks.

Typology	*Neighborhood*	*Building Height*	*Building Age*	*Building Structure*
Superblock	**Sunshine 100**	Mid-rise slabs and towers (9-18); High-rise slabs and towers (23-28)	7 years	Steel concrete
	Lvjing	Low-rise slabs (6-7); Mid-rise slabs and towers (12)	7 years	1/4 masonry-concrete, 3/4 steel-concrete
	Shanghai Garden	Low-rise slabs (6-8); High-rise towers (18)	7 years	1/2 masonry-concrete, 1/2 steel-concrete
Enclave	**Dongcang**	Low-rise slabs (6-8)	5-6 years	Mainly masonry-concrete
	Foshanyuan	Low-rise slabs (6-8)	5-6 years	Mainly masonry-concrete
	Wuyingtan	Low-rise slabs (3-8)	2-7 years	Mainly masonry-concrete, some masonry-wood
	Yanzishan	Single-story (1); Low-rise slabs (4-7); Mid-rise slabs(16); High-rise towers(27)	4-6 years	masonry-concrete
Grid	**Old Commercial District**	Single-story(1); Low-rise slabs(4-7); High-rise towers (19-32)	2-7 years	Mainly masonry-concrete, some masonry-wood
Traditional	**Zhang Village**	Low-rise detached (2-5)	3-7 years	masonry-concrete

Table 3 Neighborhood Building Attributes

Table 4 shows some important neighborhood form attributes, calculated by MIT and Beijing Normal University through GIS spatial analysis. The following patterns can be identified:

1) Although the Superblocks have more high-rise buildings, their F.A.R. and household density are not significantly higher than other neighborhoods.
2) The building function diversity in Superblocks is much lower compared to other neighborhoods, indicating a highly homogeneous residential function.
3) The superblocks have higher green space coverage and more parking spaces, which reflect higher living standard and car ownership convenience.

Attributes	Superblock			Enclave				Grid	Traditional
	Sunshine 100	Lvjing	Shanghai Garden	Dongcang	Foshanyuan	Wuyingtan	Yanzishan	Commercial District	Zhang Village
Neighborhood Size (1000 sq.m)	552.24	88.37	249.23	145.74	215.28	706.85	839.87	487.61	513.74
Floor Area Ratio (FAR)	2.15	2.12	1.81	1.94	2.22	1.16	1.97	1.69	1.19
Household Density (1000 HH_sq.km)	16.62	14.48	17.57	23.63	24.69	13.78	15.86	18.91	12.29
Average Building Height (m)	14.91	7.48	7.96	5.33	5.81	4.18	5.84	5.47	2.19
Building Function Mix[2]	0.01	0.08	0.03	0.29	0.35	0.31	0.58	0.34	0.33
Green Space Coverage[3]	38%	24%	31%	9%	27%	16%	13%	12%	0%
Road Density (km/sq.km)	25.62	32.87	27.94	21.00	22.11	23.40	15.31	23.66	29.93
Avg. Parking Area (sq.m/HH)	2.27	2.44	2.67	0.21	0.65	0.00	1.33	1.69	0.00
Distance to City Center (km)	2.50	2.80	7.30	2.30	0.80	4.60	3.50	3.60	3.00

Table 4 Neighborhood Physical Attributes

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[2] An index to evaluate the level of building function diversity, =1-((residential building area percentage -0.25) + (0.25- industrial building area percentage) + (0.25- commercial building area percentage) + (0.25- other building area percentage)) / 1.5

[3] Neighborhood green space plus road area with side trees

4.5 Summary of Household Information

Among the 2,700 questionnaires distributed, 2,631 were completed, collected and recorded into the dataset. However, the usable total is lower than that. Some responses are excluded from the analysis for the following reasons:

- One or more important variables missing: household size, household income, household type, home construction area, household electricity consumption or monthly bill, space heating type. 167 records excluded.
- Appliance ownership non-response: samples in which none of the questions related to appliance ownership is answered. 21 records excluded.
- Outlier and obvious mistake responses: household size smaller than 100 m^2 but consumes more than 500 KWH electricity per month; home size >=300 m^2 in neighborhoods other than the Traditional; worker count > HH size, etc. 101 records excluded.

After data cleaning, we arrive at the final household sample size of 2,342. **Figure 13** shows the distribution of effective household observations among the nine neighborhoods. The following sections present the sample values as aggregated to the neighborhood level and summarize the major household characteristics.

Figure 13 Composition of Effective Respondents

Household Size

Figure 14 shows the household size distribution in the nine neighborhoods. The following patterns can be observed:

1) Three persons is the most common household size in all neighborhoods except the Traditional.
2) Superblocks have more large households (size 3+) compared to other neighborhoods.
3) The Traditional has a much higher proportion of single-member households.

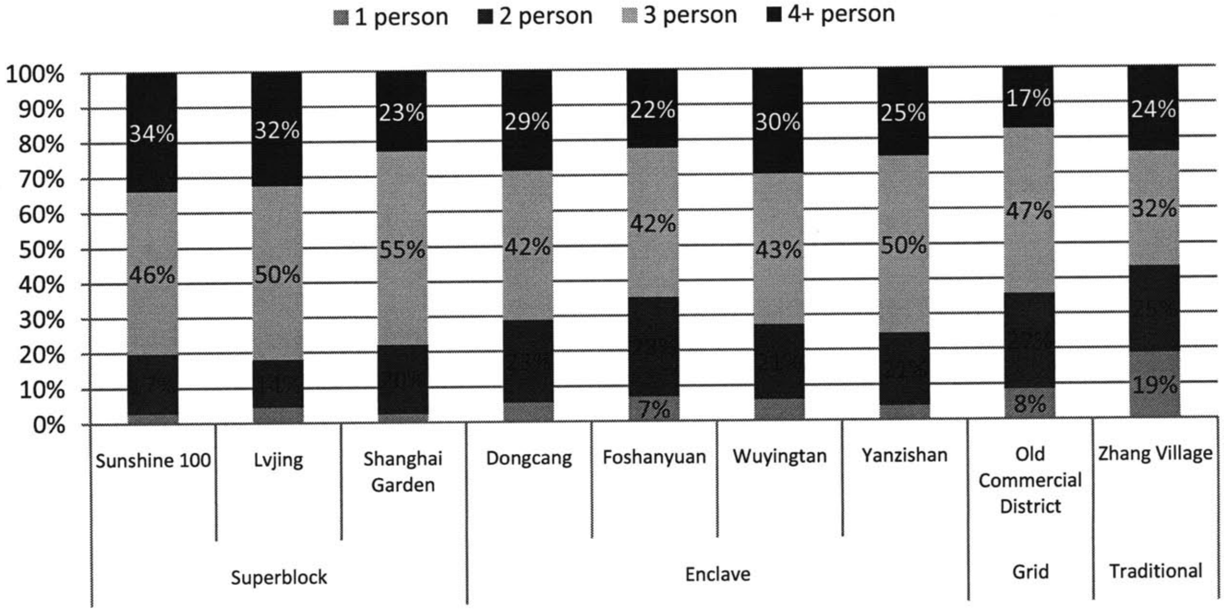

Figure 14 Household Size Share

Income

Figure 15 shows the household income distribution of the nine neighborhoods. The following patterns can be observed:

1) Superblocks have higher average household income than other neighborhoods, and the Traditional has the lowest. There is no sharp difference between Enclaves and the Grid.
2) The within-neighborhood income variance is very high in the Superblocks especially at the high end. The variance in the Traditional is much lower, indicating a more homogeneous income population group.

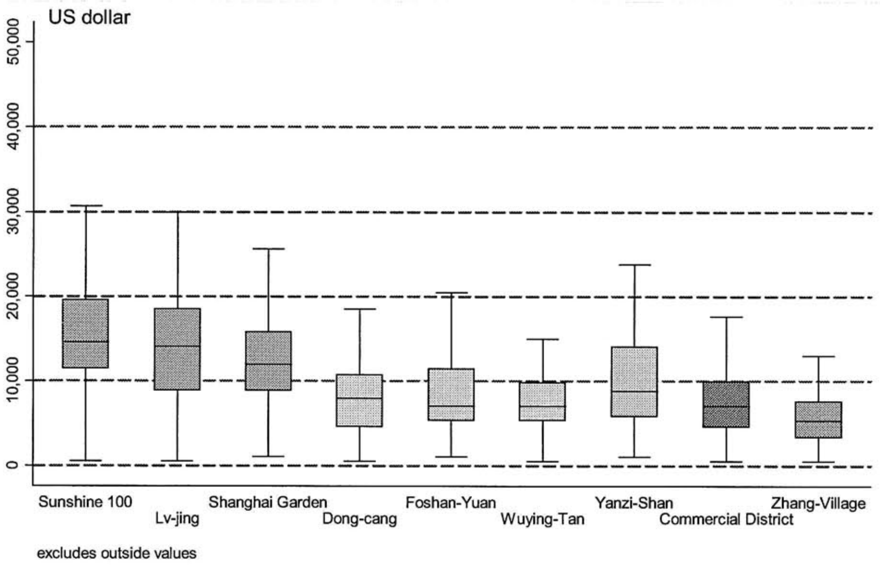

Figure 15 Household Annual Income Distribution

Figure 16 shows the share of three income groups in each neighborhood. It is clear that Superblocks are occupied dominantly by mid and high income households. The share of high income households is much smaller in Enclaves and the Grid. In the Traditional, low income households constitute the majority (60%+).

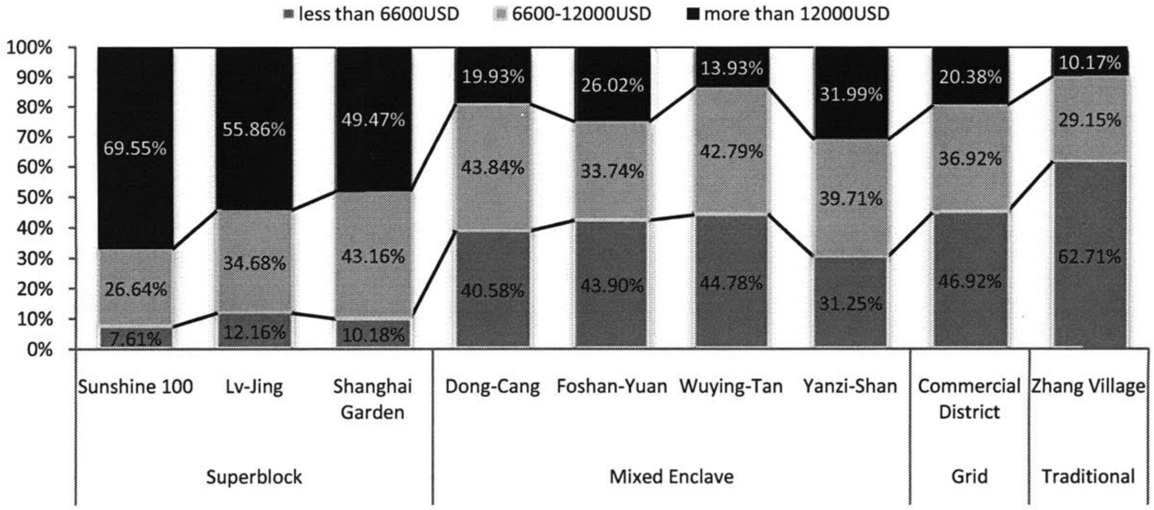

Figure 16 Household Income Share

Home Construction Area

Table 5 shows the per household average construction area of the nine neighborhoods. The Superblock households have much higher home size than that in other neighborhoods.

	Superblock			Enclave				Grid	Traditional
Neighborhood	Sunshine 100	Lvjing	Shanghai Garden	Dongcang	Foshanyuan	Wuyingtan	Yanzishan	Commercial District	Zhang Village
Average Construction Area (sqm)	127.5	139.9	108.1	66.4	71.8	64.6	70.7	70.4	73.8

Table 5 Average Home Construction Area

Figure 17 shows the share of three home size categories in the nine neighborhoods. Large-size homes clearly dominate the Superblocks, although in Shanghai Garden the share is lower than the other two. Among the Enclaves, there are barely any large-size homes, and medium-sized homes are the majority. The Grid is similar to the Enclaves. In the Traditional, however, small-sized homes make up the dominant majority, while the share of large-sized homes is also larger compared with the Enclaves and the Grid.

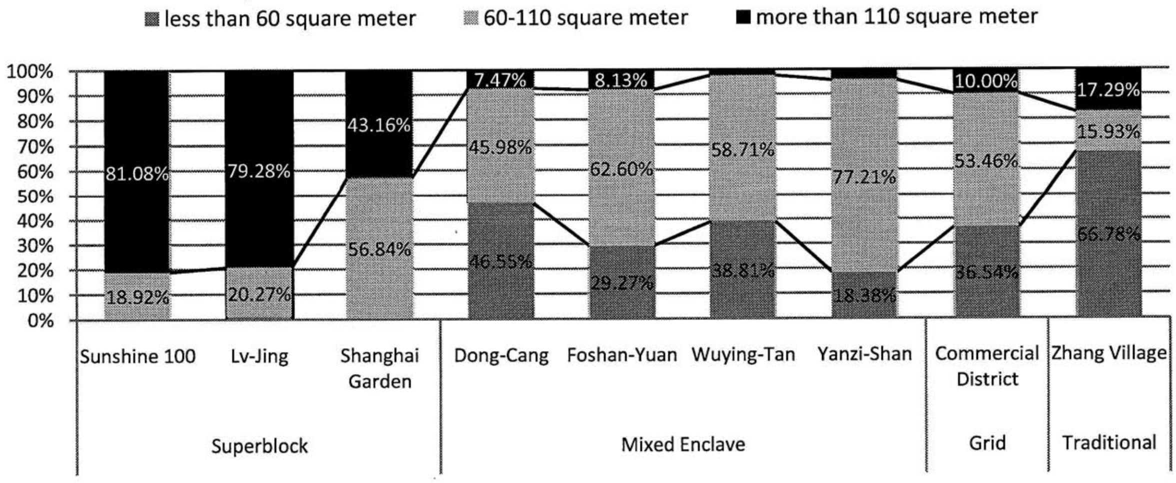

Figure 17 Home Construction Area Share

Home Ownership

Figure 18 shows the home ownership share in the nine neighborhoods. In the Superblocks, the rental share is very low and more than 90% of units are owner-occupied. Within the owner-occupied units, there is also a considerable share of homes with mortgage. For Enclaves and the Grid, the rental share is moderate, ranging from 17% to 29% and there are barely any mortgaged units. This phenomenon is in line with the welfare housing distribution system commonly applied in state-enterprise residential compounds. For the Traditional, rental units take the dominant majority and there are no mortgaged units. The high share of rental units partly explains why there is a high prevalence of single-member households in this neighborhood.

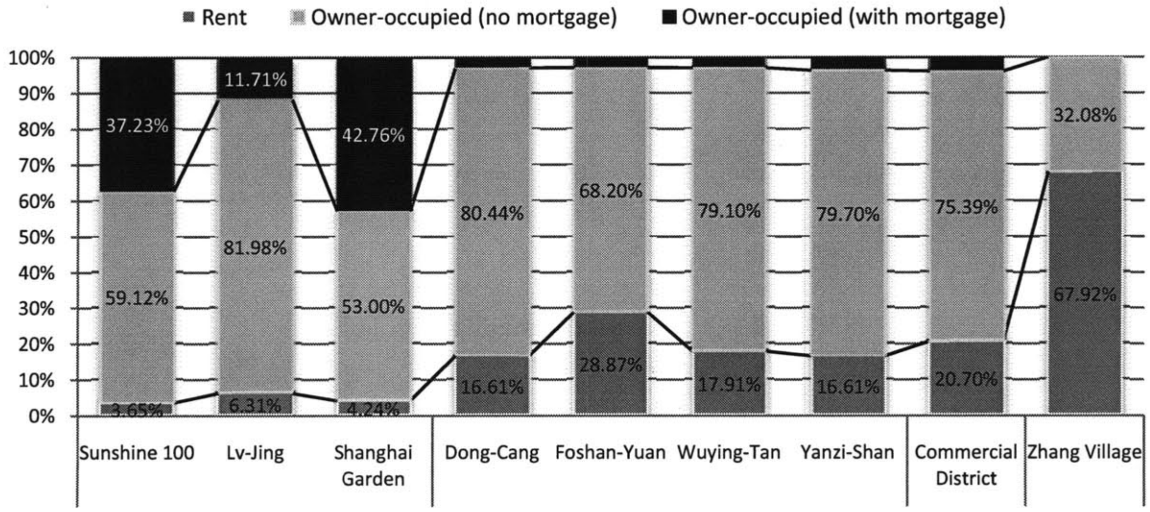

Figure 18 Home Ownership

Appliance Ownership

Figure 19 shows the air conditioner ownership share in the nine neighborhoods. The dominant majority of Superblock households own two or more ACs, while in the Traditional more than 70% of housing units do not have air conditioners at all. In the Enclaves and the Grid, most households own one AC.

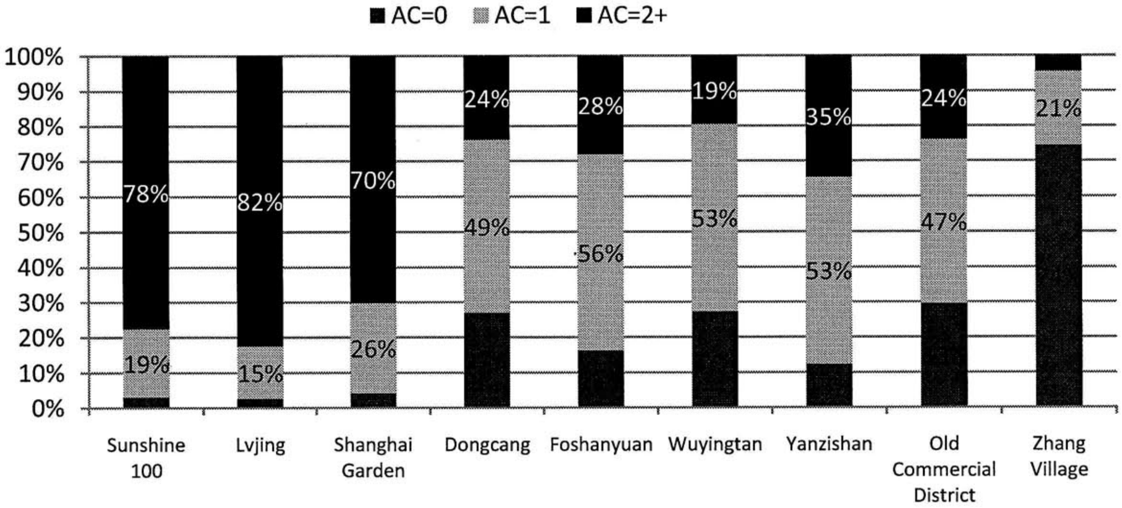

Figure 19 AC Ownership

Figure 20 shows the ownership condition of other appliances covered in the survey. The TV ownership ratio is high in all the neighborhoods, in accordance with Chinese households' traditional belief that TV is a "must-have". The refrigerator ownership ratio is also high except in the Traditional. This is most likely due primarily to the high share of rental population in this neighborhood. The desktop computer ownership ratio is higher than 80% in Superblocks, but relatively lower in other neighborhoods. Finally, the Enclaves and the Grid have higher coverage of solar water heaters, since most buildings in these neighborhoods are mid-rise. In comparison, there are barely any solar water heaters in the Superblocks, given that the limited number of top-floor units associated with high-rise buildings prevents the installation of the solar device.

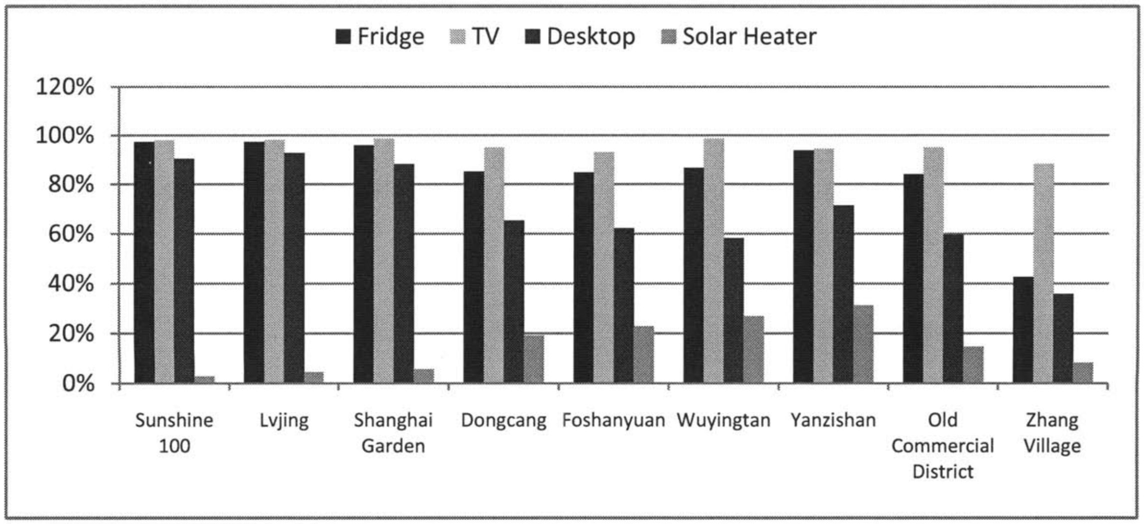

Figure 20 Appliance Ownership

Attitudes

The survey did not tap much into attitudes related to energy consumption, with only one question directly related to in-home energy using behavior ("energy saving is important"). To better instrument household consumption behavior, another attitude variable is included:

- Living in a gated neighborhood is a sign of prestige

The underlying hypothesis is that if a respondent cares more about prestige, he is likely to consume more in daily life since a "prestigious" life style is more consumptive.

Figure 21 shows the score of the two attitudes. The result does not vary significantly across neighborhoods, with a fairly neutral attitude prevailing towards "prestige" and a highly positive attitude towards "saving energy".

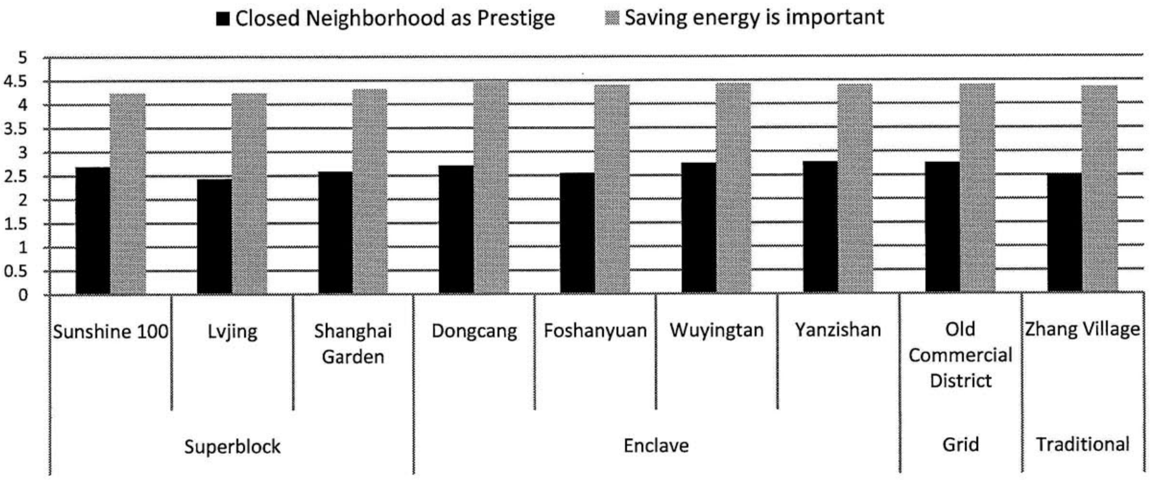

Figure 21 Attitude Score

Energy Expenditure

Figure 22 and **Figure 23** show the household total energy expenditure, the share of each energy source, and the expenditure/income ratio by neighborhood. The electricity bill takes a dominant proportion in household energy expenditure, followed by centralized heating. The expenditure share of gas and coal is relatively small. The Superblock households spend roughly 1/3 more money on energy than households in the other three types of neighborhoods, but the expenditure/income ratio does not vary much across neighborhood, except that the Traditional has obviously clearly higher ratio than all the others.

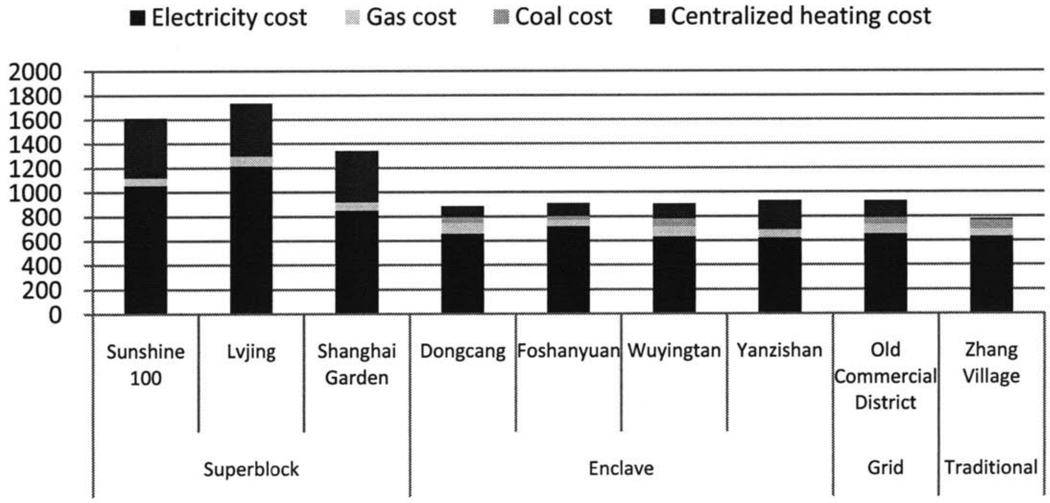

Figure 22 Household Energy Expenditure by Neighborhood

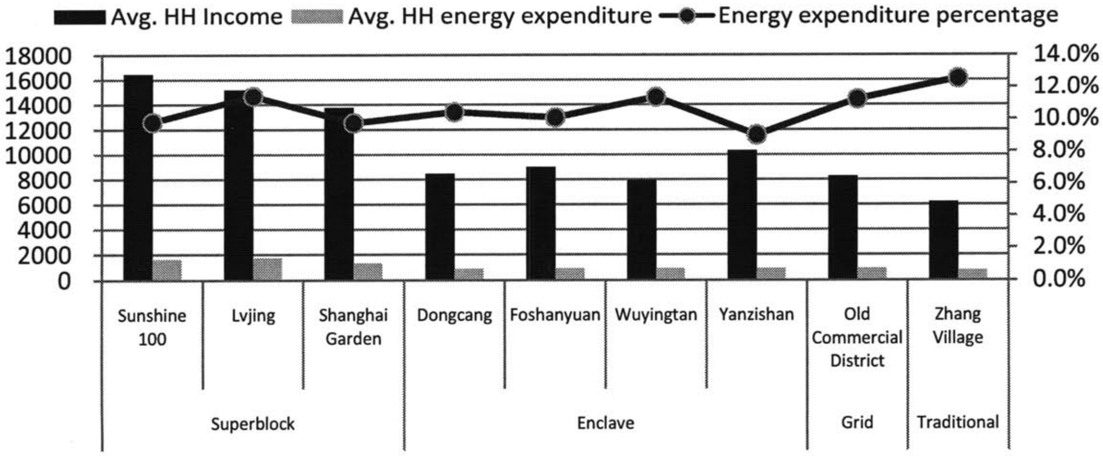

Figure 23 Household Energy Expenditure v.s. Income by Neighborhood

Figure 24 and **Figure 25** show the household total energy expenditure, the share of each energy source, and the expenditure/income ratio by three income groups. As household income increases, energy expenditures rise and the share of centralized heating increases while the share of coal decreases. The expenditure/income ratio decreases with income increase. The ratio is 20.3% for the low-income group but only 7.5% for the high-income group.

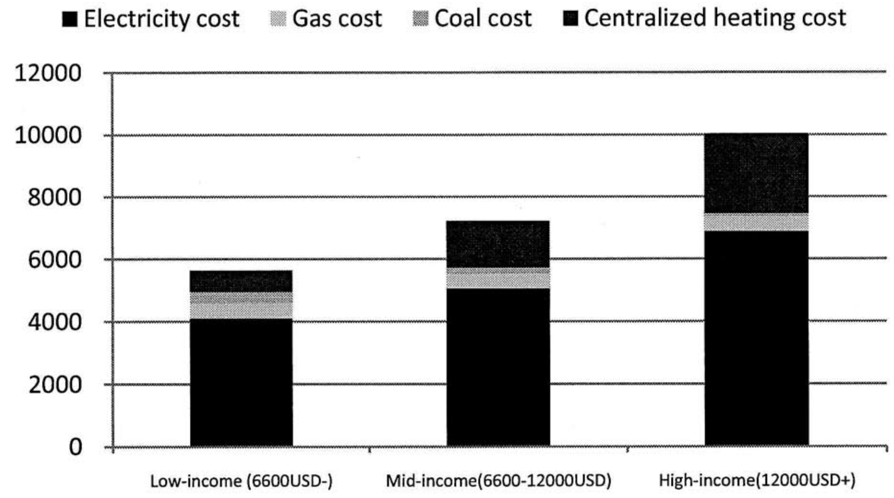

Figure 24 Household Energy Expenditure by Income Group

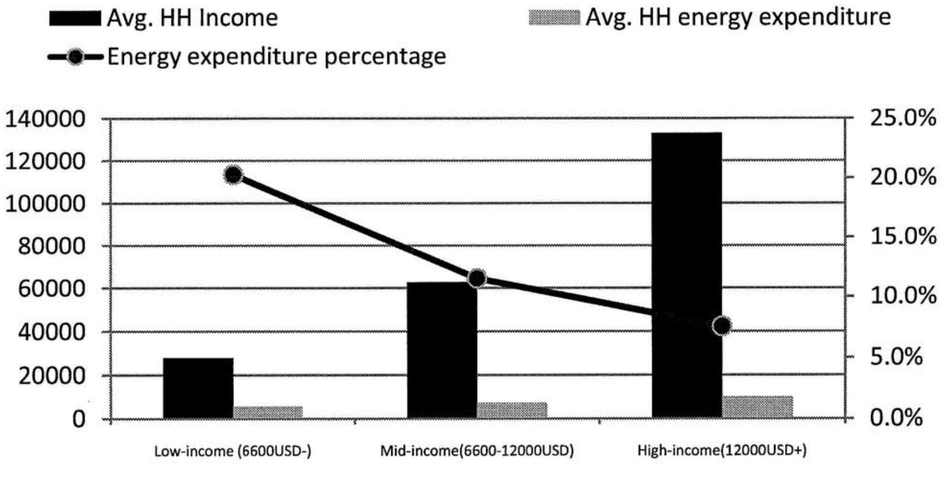

Figure 25 Household Energy Expenditure vs. Income by Income Group

Chapter 5: Household Energy Consumption and GHG Emission Pattern

5.1 The Composition of Household Energy Consumption

For households in Jinan, there are four types of energy for in-home use: electricity, gas, coal, and centralized heating. Note that these four energy sources should all be considered as "secondary". Electricity and centralized heating are generated from coal. The coal briquettes consumed in households are also "secondary", since it is transformed from raw coal. So is the case for gas, which is transformed to LNG, LPG or coal gas from raw primary gas, oil, or coal.

Among the 2342 effective survey respondents, 100% use electricity, 80.6% use gas, 18.4% use coal, and 56.1% use centralized heating. The usage of the four types of energy is summarized in **Table 6**. As shown in the table, there are overlapping uses across different types of energy, such as space heating, water heating and cooking. Take space heating for example, if a household lives in a building not covered by centralized heating, it can choose either to use coal or electricity for space heating. Notably, more than one energy type might apply simultaneously to one use. If a household prefers warmer in-home temperature than the centralized heating system can provide, it will choose to use extra electric heaters or ACs as supplements.

Energy Type	***Possible Uses***
Electricity	Electronic appliances, lighting, space heating and cooling, water heating
Gas	Cooking, water heating
Coal	Space heating, water heating, cooking
Centralized heating	Space heating

Table 6 Energy Types and Possible Uses

5.2 Energy Consumption Calculation Method

The household energy consumption data obtained from the survey are:

1) Monthly electricity consumption amount (KWH) or bill.
2) Gas type and monthly gas consumption amount (cubic meter) or bill.
3) Annual coal consumption amount (ton) or bill.

For each energy source, the energy consumption and the GHG emission are calculated, using the methodology described below. Note that for electricity and centralized heating, the calculation result includes the primary energy consumed for power generation, and accounting for all conversion and transmission losses. For gas and coal that are consumed on-site, the calculation only accounts for the total energy contained in the secondary forms (LPG, LNG, coal gas, and coal briquettes).

Electricity

The equation to calculate electricity energy consumption (E_e) in megajoules (MJ):

$$(14)\quad E_e = \frac{B_e * 12}{P_e} * q_e \div (1-\beta) \div \varepsilon$$

Symbol	Description	Value	Unit
B_e	Household monthly electricity bill	Input	Yuan RMB
P_e	Electricity price[4]	0.5469	Yuan/KWH
q_e	Thermal-electricity conversion factor	3.6	MJ/KWH
β	Electricity transmission loss rate[5]	7.08%[6]	
ε	Coal power plant conversion rate[7]	35.47%[8]	

Table 7 Electricity Energy Consumption Parameters

The calculation result implies the total energy consumed to generate the given amount of electricity used by the household, including the power plant conversion losses and the grid transmission losses.

---

[4] Source: Jinan Electricity Bureau
[5] Source: State Electricity Regulatory Commission, China
[6] National average
[7] Source: China Energy Yearbook 2009
[8] Shandong Province average

Gas

There are three types of gas consumed in Jinan: LNG, LPG and coal gas.

The equation to calculate gas energy consumption (E_g) in megajoules (MJ):

$$(15)\ E_g = \frac{B_g * 12}{P_g} * \gamma_g$$

Symbol	Description	Value	Unit
B_g	Household monthly electricity bill	Input	Yuan RMB
P_g	LNG unit price	2.4	Yuan/m^3
	Coal gas unit price	1.3	Yuan/m^3
	LPG unit price	13.9	Yuan/m^3
γ_g	LNG unit thermal value	36.4	MJ/m^3
	Coal gas unit thermal value	16.74	MJ/m^3
	LPG unit thermal value	118.2	MJ/m^3

Table 8 Gas Energy Consumption Parameters

The calculation result implies the total energy contained in the specific amount of gas consumed by the household, including the actual heat produced and the incomplete combustion losses.

Coal

The equation to calculate household coal energy consumption (E_c) in megajoules (MJ):

$$(16)\ E_c = \frac{B_c}{P_c} * \gamma_c$$

Symbol	Description	Value	Unit
B_c	Household annual coal bill	Input	Yuan RMB
P_c	Coal unit price[9]	876	Yuan/ton
γ_c	Coal unit thermal value[10]	26700	MJ/ton

Table 9 Gas Energy Consumption Parameters

The calculation result implies the total energy contained in the specific amount of coal consumed by the household, including the actual heat produced and the incomplete combustion losses.

---

[9] Source: Jinan Price Bureau

[10] Source: Jinan Public Utilities Bureau

Centralized Heating

As mentioned, the centralized heating fee is charged on a construction-area basis rather than on the actual heat consumed. Thus the heating bill does not reflect the actual heat consumed by the household. As such, the centralized heating energy consumption can only be calculated based on the construction area of the household.

The equation to estimate centralized heating energy consumption (E_{ch}) in megajoules (MJ):

(17) $E_{ch} = 86.4 * N * A * q_h * \frac{t_i - t_a}{t_i - t_{o.h}} \div \mu_b \div \mu_p$ [11]

Symbol	Description	Value	Unit
A	Home construction area	Input	m^2
N	Heating days per year[12]	140	day
q_h	Building heating index[13]	33.16[14]	W/m^2
t_i	Indoor designed temperature during heating period[15]	18	°C
t_a	Average outdoor temperature during heating period[16]	-0.9	°C
$t_{o.h}$	Outdoor designed temperature during heating period[17]	-7	°C
μ_b	Cogeneration boiler efficiency[18]	0.87	
μ_p	Pipe network efficiency[19]	0.98	

Table 10 Centralized Heating Energy Consumption Parameters

The calculation result implies the total energy consumed to generate the given amount of centralized heat used by the household, including the heat plant conversion losses and the pipeline transmission losses.

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[11] Source: Practical Handbook for Centralized Heating. Li et al. 2006
[12] Source: Jinan Heat Power Company, Jinan
[13] Source: Gao, et al. 2008
[14] Jinan average
[15] Source: Jinan Public Utilities Bureau
[16] Source: Jinan Public Utilities Bureau
[17] Source: Jinan Public Utilities Bureau
[18] Source: Jinan South Suburban Cogeneration Plant
[19] Source: Jinan South Suburban Cogeneration Plant

5.3 In-home Energy Consumption Pattern

Using the methodology described above, the energy consumption for each household participating in the survey is calculated, and then aggregated to the neighborhood scale to enable cross neighborhood comparison.

Total Energy Consumption

Figure 26 shows the consumption share of the four energy sources in each neighborhood. In Superblock neighborhoods, no household uses coal. The dominant energy sources are electricity and centralized heating, each accounting for 40% to 50% percent of neighborhood total energy consumption. In Enclave and Grid neighborhoods, households' choices of energy source are more diverse. Coal is widely used for space heating purpose, and it replaces part of the centralized heating energy consumption. In the Traditional neighborhood, very few households can access centralized heating so coal consumption takes over. Compared to the consumption of centralized heating and coal, the consumption share of gas is more stable around 10%, with the share in Enclave and Grid slightly higher than in the other two types of neighborhoods.

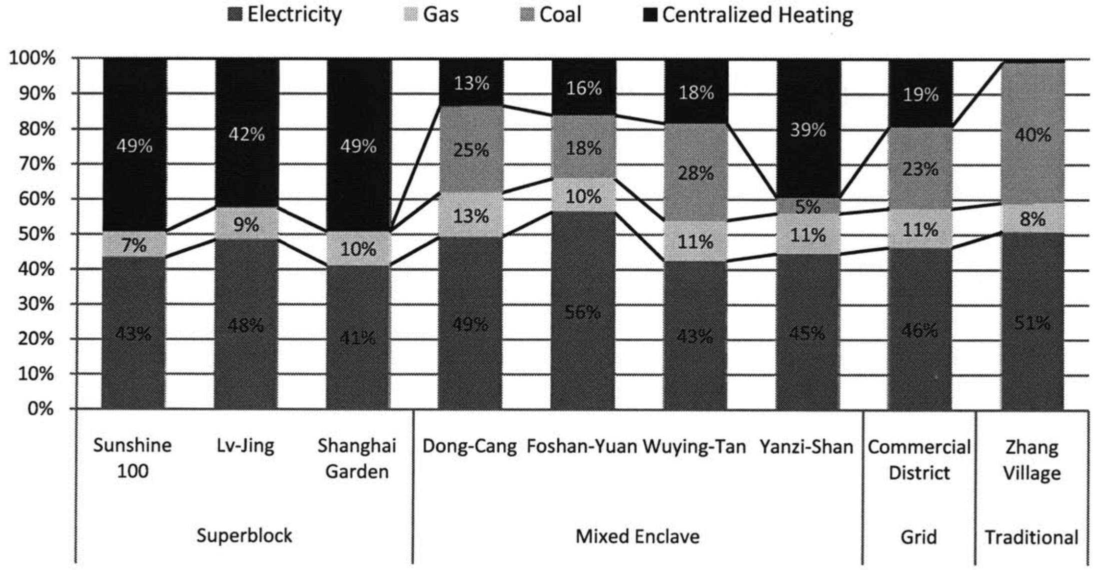

Figure 26 Household In-home Energy Consumption Share by Source

Figure 27 shows per household and per capita total energy consumption of the nine neighborhoods. The Superblocks consume much more energy, approximately 40% to 50%, compared to the other three neighborhood typologies, whether measured by household or per capita. There is little difference between the Enclaves and the Grid on a per household basis. On a per capita basis however, the Grid consumes more than the Enclaves. The Traditional consumes the least energy among all neighborhood types on a per household basis. But on a per capita basis, there is little difference between the Traditional and the Enclaves.

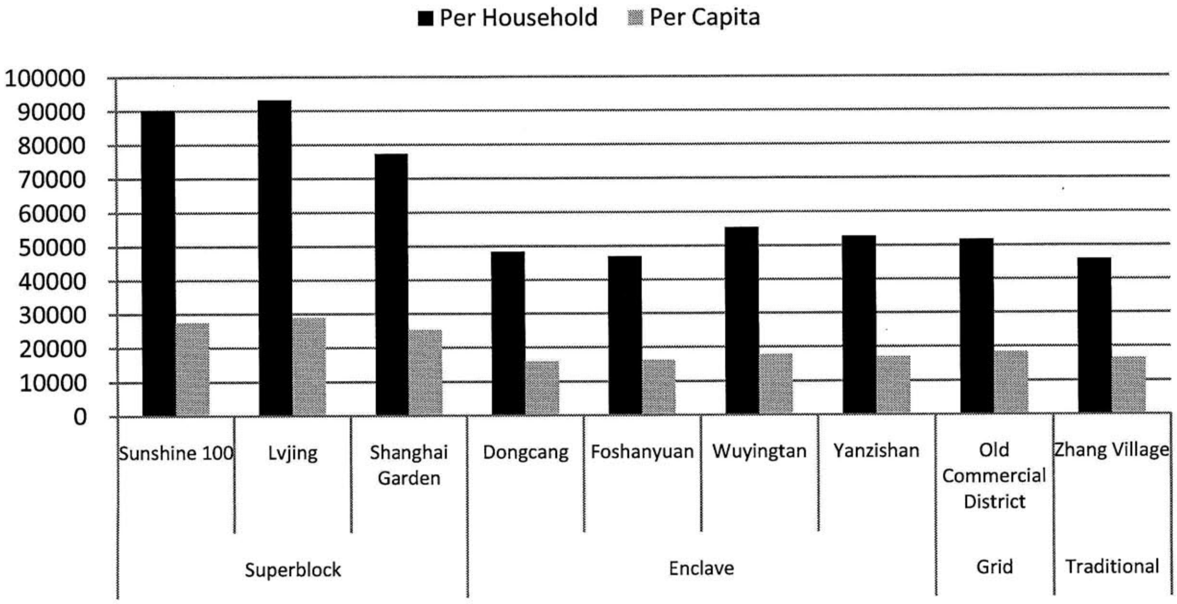

Figure 27 Annual In-home Energy Consumption per HH and per Capita (MJ)

Figure 28 shows the range of per household energy consumption of the nine neighborhoods. The consumption range is large for all neighborhoods, indicating vast variation in energy consumption patterns among households in the same neighborhood. The range is especially large in Lv-jing (Superblock) and Zhang Village (Traditional). For Zhang Village, the range of the upper end is much larger than that of the lower end.

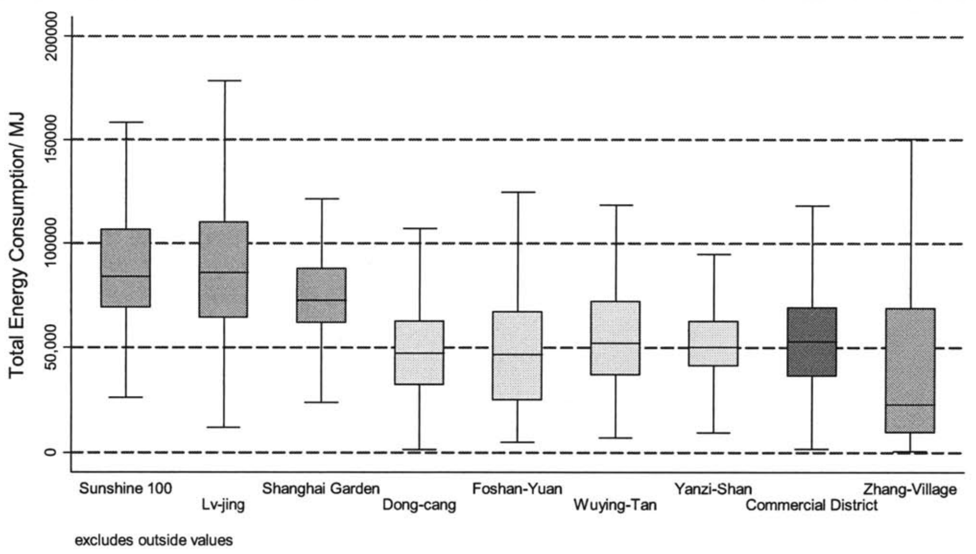

Figure 28 Household Energy Consumption Distribution

Figure 29 shows per square meter construction area total energy consumption of the nine neighborhoods, marked by the average construction area per household. The consumption pattern is the opposite compared to that on per household basis. On per square meter basis, Superblocks consume slightly less energy than the Grid and three of the four Enclaves. The Traditional is again the least energy-intensive, with 634 MJ/m^2 consumed annually.

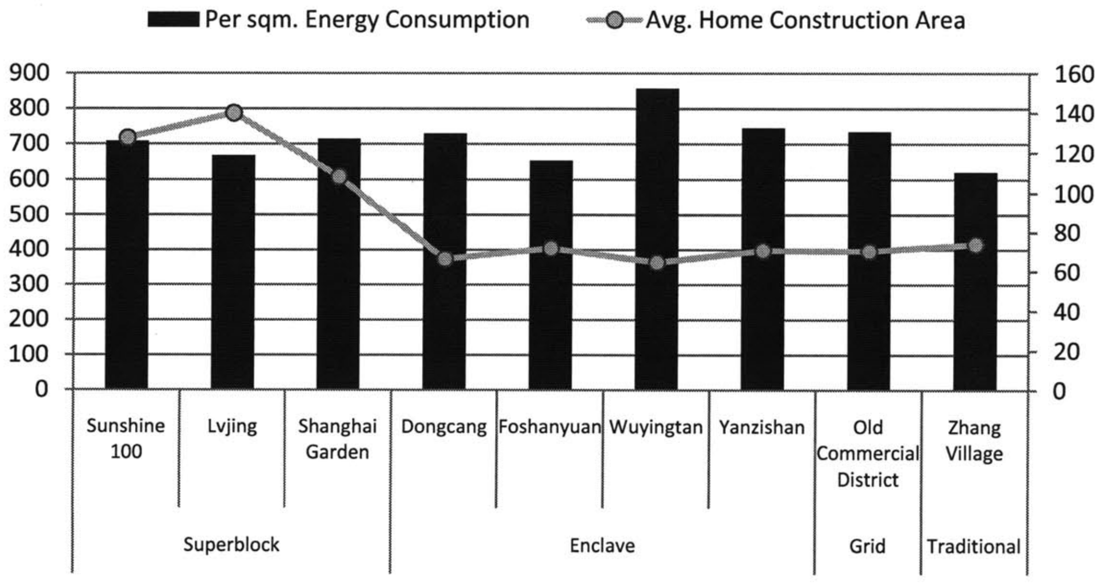

Figure 29 Annual In-home Energy Consumption per Square Meter (MJ)

Electricity

Figure 30 shows per household, per capita, and per square meter electricity energy consumption of the nine neighborhoods. The consumption pattern is similar to that of total energy consumption. The Superblocks consume more electricity on a per household and per capita basis, while the Enclaves and the Grid consume more on a per square meter basis. Once more, the Traditional is the least electricity-intensive.

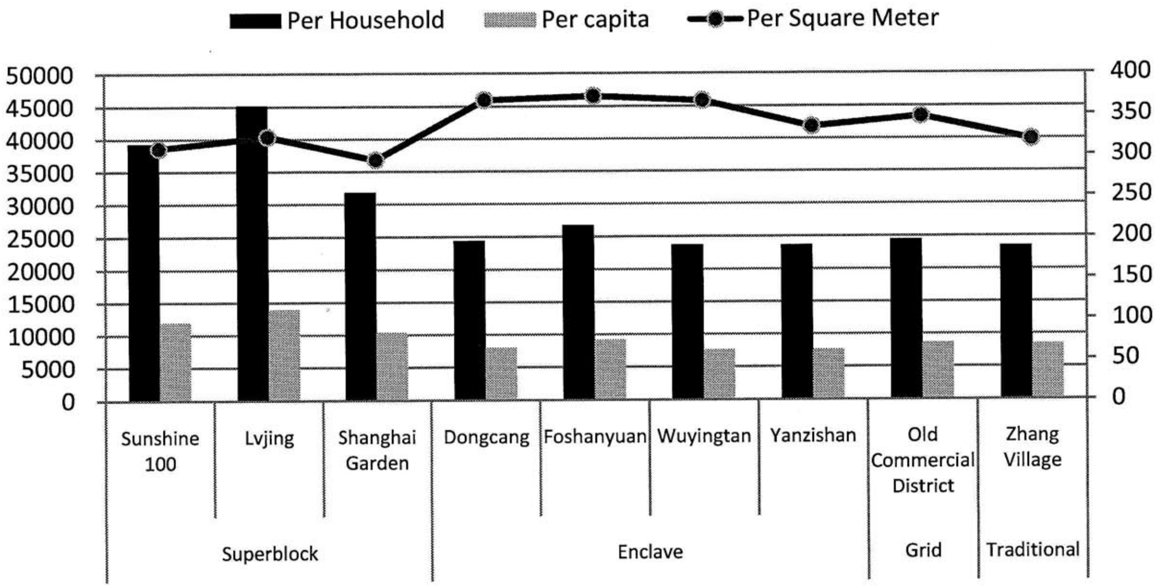

Figure 30 Annual Electricity Energy Consumption (MJ)

Gas

Figure 31 shows per household and per capita gas energy consumption of the nine neighborhoods[20], including LPG, LNG and coal gas. Although the gas sources vary across neighborhoods, the total gas consumption does not have much variance.

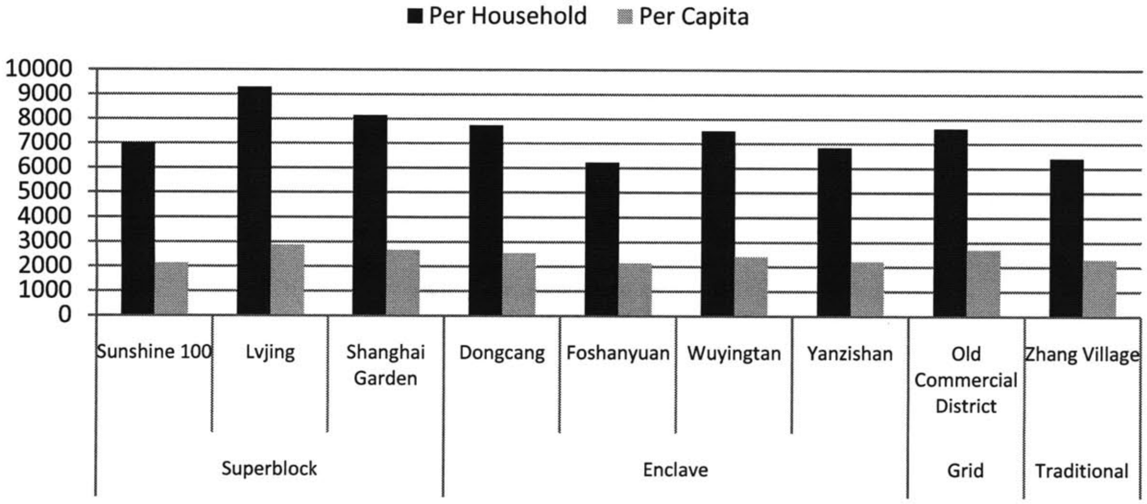

Figure 31 Annual Gas Energy Consumption (MJ)

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[20] Sub-sample only includes households using gas.

Coal

Figure 32 shows per household, per capita, and per square meter coal consumption of the six neighborhoods using coal[21]. The three superblocks are not included. The Traditional consumes the largest amount of coal on per household basis, followed by Wuyingtan, which is exceptionally higher compared to other Enclaves. The Grid also consumes more than the three Enclaves. On per capita basis, the top three are Wuyingtan, the Grid and the Traditional. On per square meter basis, the Traditional turns out to be the least coal-intense, but the consumption of Wuyingtan and the Grid remains the highest among all neighborhoods.

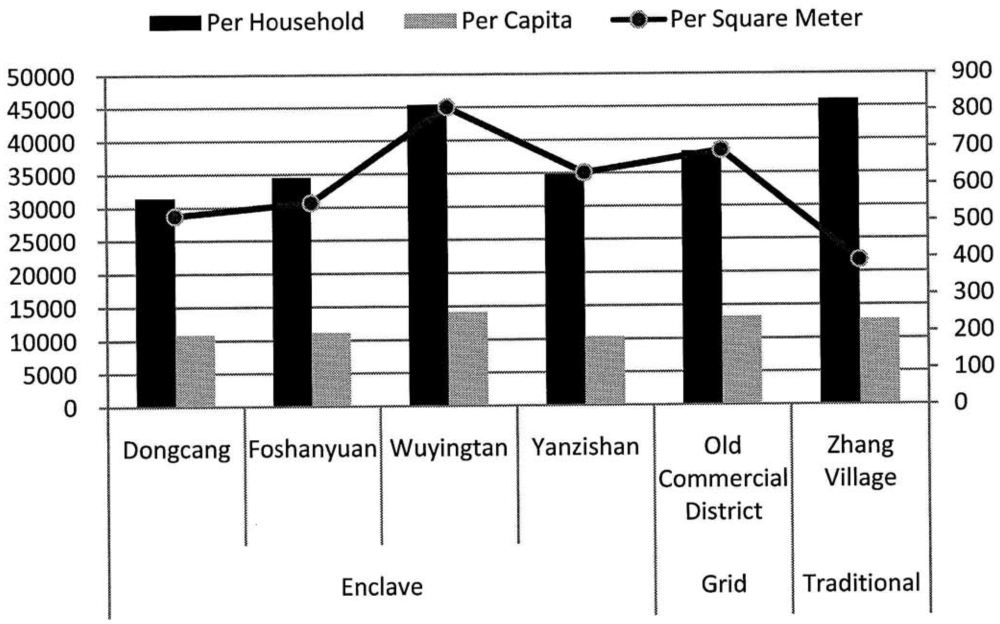

Figure 32 Annual Coal Energy Consumption (MJ)

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[21] Sub-sample only includes households using coal.

Centralized heating

Figure 33 shows per household and per capita centralized heating energy consumption of the eight neighborhoods with at least 10% centralized heating coverage[22]. Again, since the centralized heating energy consumption is estimated upon the construction area of the home, the result only reflects the variance in the home sizes of centralized heating users across different neighborhoods. Not surprisingly, the Superblocks consume much more than the Enclaves and the Grid, since their average home size is much larger.

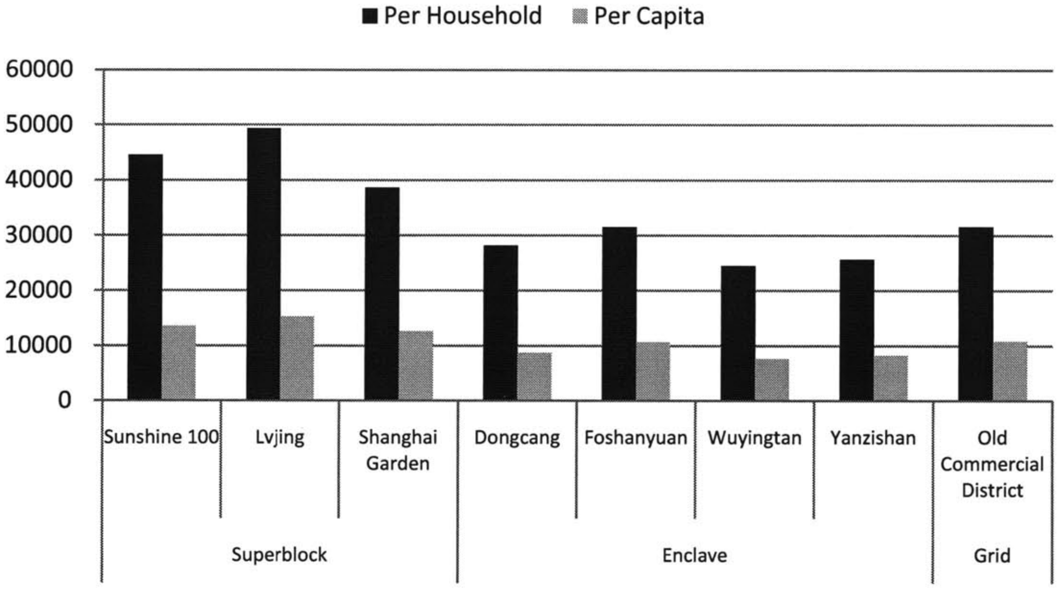

Figure 33 Annual Centralized Heating Energy Consumption (MJ)

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[22] The Traditional is excluded because only 6 households in the neighborhood use centralized heating

5.4 GHG Emission Calculation Method

The calculation of GHG emission uses the recommended Tier 1 methodology developed by the Intergovernmental Panel on Climate Change (IPCC), according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The equation is as follows:

$$GHG_{fuel} = E_{fuel} * EF_{fuel} \quad (18)$$

Where GHG_{fuel} is the GHG emission of a certain fuel, E_{fuel} is the amount of fuel combusted (J), and EF_{fuel} is the default emission factor. A full set of values for EF_{fuel} is provided by the IPCC, and the information extracted for the calculation purpose is summarized in **Table 11**.

Fuel	**Bituminous Coal**	**Anthracite Coal**	**Natural Gas**	**LPG**	**Coal Gas**
IPCC Category	Energy Industries	Residential	Residential	Residential	Residential
EF_{fuel} (ton/TJ)*	94.6	98.3	56.1	63.1	44.4
Associated HH Energy Source	Electricity Centralized Heating	Household Coal	Gas	Gas	Gas

* The emission factor includes CO_2 and equivalent

Table 11 GHG Emission Factors

For Shandong Province, more than 99% of electricity and 100% of centralized heating is produced from coal. In the calculation, we assume that all coal used in energy industries is bituminous coal, and it supports 100% of electricity and centralized heating production. For comparison, the anthracite coal used in the residential sector is of higher quality, and with a slightly higher EF_{fuel} value.

5.5 GHG Emission Pattern

Using the IPCC methodology, the GHG emission of each household is calculated based on the energy consumption value obtained from the previous section, and then aggregated to the neighborhood level.

Total GHG Emission

Figure 34 shows the total GHG emissions of the nine neighborhoods on per household, per capita, and per square meter basis. The emission pattern is very similar to the energy consumption pattern. The Superblocks have much higher emissions compared to other neighborhoods both on per household basis and per capita basis, with the emissions of Sunshine 100 and Lvjing reaching 8 metric ton/household. The emission per household and per capita does not vary much across Enclaves, Grid and Traditional, all falling within the range of 4-5 metric ton/household. On per square meter basis, there is no significant difference among neighborhoods.

Overall, the average GHG emission of the 2342 samples is 5.8 metric ton per household and 1.9 metric ton per capita. The emission intensity is about one-half of the US household emission level, which is around 4 metric tonnes per capita (EPA, 2010).

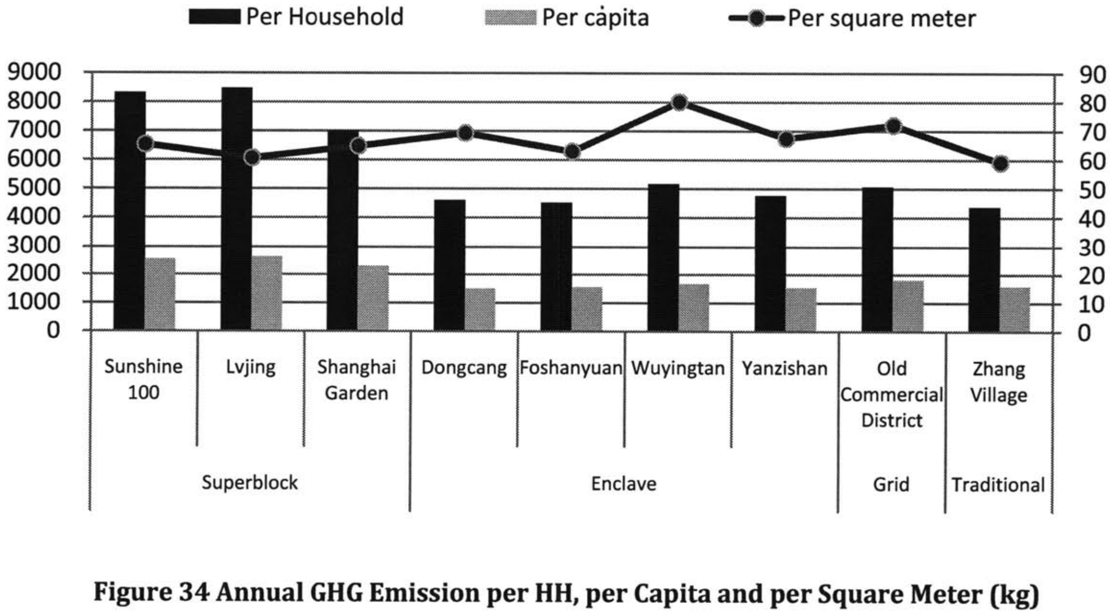

Figure 34 Annual GHG Emission per HH, per Capita and per Square Meter (kg)

Figure 35 shows the GHG emissions share of different energy sources. Again, the pattern is similar to the energy consumption share by energy sources (**Figure 26**), and the only difference is the smaller share of gas, due to its relatively smaller GHG emission factor compared to coal. According to the figure, it is clear that in the residential sector of Jinan, more than 90% of household in-home GHG emission is caused directly or indirectly by coal.

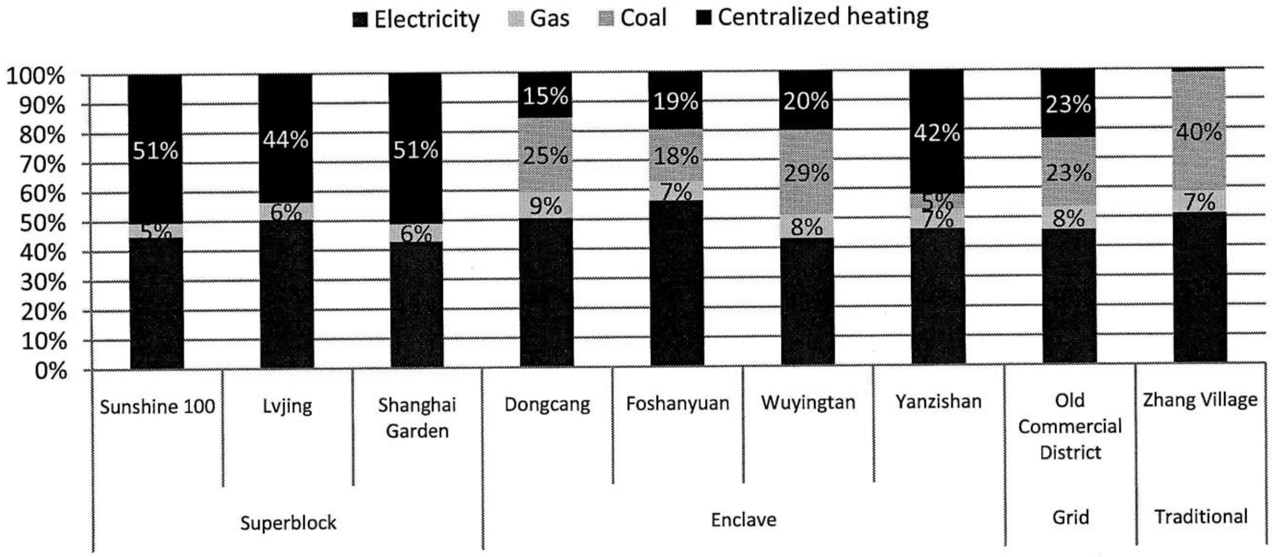

Figure 35 GHG Emission Share by Household Energy Source

Chapter 6: Modeling In-home Energy Consumption and GHG Emissions: Multivariate Analysis Results

6.1 Overview

Using the empirical data obtained from the household survey, we can model the household in-home energy consumption and GHG emission using regression methods. This chapter starts from analyzing household energy source choice, with the coal choice model presented. Then the home appliance choice models are constructed, providing insight into the discrete choices upon which the energy consumption takes place. In the third step, the energy consumption and GHG emission models for the three individual energy sources – electricity, coal and gas – are constructed, with the 2-stage OLS modeling approach tested to control for potential endogeneity. Finally, the models for total energy consumption and GHG emission are developed and discussed.

Table 12 presents the variables used, their abbreviations, descriptions and mean values.

Variable	Description	Mean	S.D.
Category 1: Socio-demographics			
LN_(HHincome)	the log transformed household income in 1,000RMB	4.04	0.74
Adult_1	=1 if the household has 1 adult	7.3%	
Adult_2	=1 if the household has 2 adults	64.7%	
Adult_3+	=1 if the household has 3 or more adults	28.0%	
Kid	=1 if the household has 1 or more kids	67.3%	
Elderly	=1 if the household has 1 or more elderly	20.8%	
Rent	=1 if the household lives in a rental unit	21.5%	
Category 2: Attitudes			
Attitude_prestige	=1 if the household agree or strongly agree that living in closed neighborhood is a prestige	20.8%	
Attutide_savingenergy	=1 if the household agree or strongly agree that it cares about saving energy	83.5%	
Category 3: Home Physical			
LN_area	the log transformed home construction area of the household	4.31	0.62
Top_floor	=1 if the household lives on top floor housing units	10.0%	
Bedroom_1	=1 if the household’ s home has 1 bedroom	19.1%	

Bedroom_2	=1 if the household’ s home has 2 bedroom	48.9%	
Bderoom_3+	=1 if the household’ s home has 3 or more bedrooms	32.0%	
Category 4: Energy Source and Usage			
Gas	=1 if the household uses gas	80.6%	
Coal	=1 if the household uses coal	18.4%	
Centralized_heating	=1 if the household uses centralized heating	56.1%	
Electricity_heating	=1 if the household uses electricity heating	18.5%	
Electricity_energy_consumption	Household total electricity energy consumption	29095	22372
Gas_energy_consumption	Household total gas energy consumption	7353	5637
Coal_energy_consumption	Household total coal consumption	39560	22463
E+G+C_energy_consumption	Household sum of electricity, gas and coal energy consumption	42287	30529
E+G+C_GHG_emission	Household sum of electricity, gas and coal GHG emission	3802	2875
Category 5: Appliance Ownership			
AC_0	=1 if the household has no AC	22.3%	
AC_1	=1 if the household has 1 AC	37.1%	
AC_2+	=1 if the household has 2 or more ACs	40.6%	
TV_0	=1 if the household has no TV	4.7%	
TV_1	=1 if the household has 1 TV	75.7%	
TV_2+	=1 if the household has 2 or more TVs	19.6%	
Fridge	=1 if the household has 1 or more fridge	84.7%	
Desktop	=1 if the household has 1 or more desktop	69.5%	
Solar_WH	=1 if the household has 1 or more solar water heater	15.1%	
Category 6:Building Type			
Low_rise	=1 if the household lives in a low-rise building (1-3 stories)	12.7%	
Mid_rise	=1 if the household lives in a mid-rise building (4-12 stories)	78.6%	
High_rise	=1 if the household lives in a high-rise building (13+ stories)	8.6%	
Category 7: Neighborhood Typologies			
Superblock	=1 if the household lives in the Superblock	34.0%	
Enclave	=1 if the household lives in the Enclave	42.4%	
Grid	=1 if the household lives in the Grid	11.1%	
Traditional	=1 if the household lives in the Traditional	12.6%	

Table 12 Abbreviations of Variables

6.2 Energy Source Choice Model

The household energy source choice has significant impact on household energy consumption and GHG emission, given the variation of carbon intensity and equipment efficiency associated with certain types of energy use. The residential sector in China is dominated by multifamily apartment buildings. All housing units developed within a residential cluster normally have identical design of energy uses, and households have very limited freedom to change the existing setting, either due to technical impossibility or regulation control. In other words, the home energy source choice is in most cases "embodied" in the housing choice. Instead of choosing what energy to consume alone, the household is making a bundle of choices at one time, including location, convenience, affordability, etc.

Coal is, more or less, an exception to the bundled housing and energy source choice in China. Although on-site consumption of coal is rapidly diminishing in the Chinese urban residential sector, it is still the primary energy source for space heating in many older residential neighborhoods constructed before 1990s, as well as in the urban villages. In residential buildings without centralized heating, households have two heating choices: coal or electricity. The household coal stove is a simple device and relatively easy to install in low-rise and mid-rise buildings. Thus, households in such buildings can choose to use coal and/or electric heating appliances, such as air-conditioners or electric heaters. I hypothesize that household attributes and neighborhood physical attributes have significant impact on households' decision about whether to use coal or not, and the relationship is tested through binary logistic choice models, as introduced in the methodology section (Equation (10), Section 3.3)

Specifically, in the coal choice model I use building height dummies rather than the four neighborhood typology dummies to examine neighborhood physical form impact. The reason is that within all neighborhood physical attributes, building type is the factor that might most affect household's choice of coal use, considering the difficulty of coal briquette delivery and fire safety concerns. More detailed explanation will be provided following the model results.

In the Superblocks, all households have either a centralized heating connection or electric floor-heater installed. Households cannot switch to other energy sources; no coal is consumed in these three neighborhoods. In the other six neighborhoods, however, centralized heating coverage is limited and the choice of coal becomes relevant. Accordingly, the binominal logistic model uses the 1524 household records from the Enclaves, the Grid and the Traditional as the sample. The regression result is shown in **Table 13**.

Variables	Coefficient		Z-test	Sig.	Odds Ratio
HHincome_100USD	**-0.026**	***	22.299	0.000	0.975
Adult_1	ref.				
Adult_2	**0.615**	**	4.786	0.029	1.850
Adult_3+	**0.876**	**	6.329	0.012	2.402
Elderly	**0.680**	***	6.807	0.009	1.974
Kid	**0.348**	**	4.404	0.036	1.416
Rental	**-2.027**	***	99.603	0.000	0.132
Attitude_prestige	0.062		0.115	0.735	1.064
Attitude_saveenergy	-0.060		0.081	0.776	0.942
Homesize65sqm_less	**0.496**	***	9.217	0.002	1.643
Lowrise	**0.811**	***	17.786	0.000	2.250
CentralizedHeating	**-4.198**	***	128.526	0.000	0.015
(Constant)	-0.526		2.238	0.135	
No. Observations	1527				
Coal Use=Yes	420		27.5%		
Chi Square	632.296				
Log Likelihood(Intercept)	1567.260				
Log Likelihood(Final)	934.964				
Pseudo R2	0.352				

p*<0.1, p**<0.05, p***<0.01

Table 13 Binary Logit Model of Household Choice of Coal Use

The choice model results suggest:

- Households with higher income are less likely to use coal as an in-home energy source. The finding supports the hypothesis that coal is an inferior good associated with lower price, but also lower convenience and lower safety level. Low-income households will prefer coal given their tight budget constraint.

- The impact of household size on coal choice is significant. Households with more adults are more likely to use coal. The rationale is that using coal is troublesome: transporting the coal briquettes and operating the coal stove involves considerable labor work. Single-person households are less likely to use coal due to time and labor constraint. Also, holding household income constant, large households have higher incentive to save energy expenditure because they have more demands to satisfy. So they are more likely to use coal, the cheap energy source.

- Households with elderly are more likely to use coal, perhaps because old residents are familiar with this traditional energy source and are unlikely to change to other alternatives.

- Having children increases the likelihood that a household uses coal, since having children increases the household size thus making coal use more cost-effective. The result also suggests that Chinese households currently do not pay enough attention to children's health. The two attitude variables are not significant in the model. It is also possible that the two variables do not effectively reflect households' lifestyle difference.

- Households living in small homes (construction area less than 65 m^2) are more likely to use coal than those living in larger homes. The current coal stoves used in Chinese households normally heat the entire home area, which becomes increasingly difficult as the home size increases. For owners of large homes, using ACs or electric heaters in separate rooms may be more cost effective. According to a simplified calculation, heating a 100 m^2 room will cost 2700RMB (24-hour heating) using centralized heating and cost 1400RMB (assuming 10 hours heating per day) using coal. If using two 800W electric heaters in two separate rooms, the cost would be around 1,300RMB (assuming 10 hours operation per day on 60% actual power). If the home size is larger, using coal would be more costly.

- Households choosing to live in low-rise buildings are more likely to use coal. The coal briquettes, as the most common form of coal used in Chinese households, need to be lifted up to the floor on which the households live. This may dissuade households in mid-rise and high-rise buildings from using coal. Also, installing a coal stove in mid-rise and high-rise buildings is in some cases technically infeasible, given ventilation and fire prevention concerns.

- Finally, a household's access to centralized heating reduces the likelihood of using coal. This makes intuitive sense as the two are largely substitutes with regard to space heating. If a household uses both, coal is probably used to complement centralized heating, or to serve other purposes such as cooking and/or water heating.

To summarize, household socio-demographics, attitudes and home and building physical attributes all influence households' energy source choice for coal. But again, it should be emphasized that the household energy source choice is within the housing choice bundle, even if the choice of using coal or not can be considered independent to some extent. Some socio-demographic attributes, such as income, undoubtedly influence people's housing choice, which might have the energy source choice embodied. A potential endogeneity problem exists in the model. But, since the data collected in the survey do not allow us to model people's housing choice, we cannot currently model this undoubtedly more complex decision-making process.

Nevertheless, based on the current result we are able to confirm the impact of neighborhood form on household energy choice. The dominant majority of low-rise buildings (1-3 stories) exist in the Traditional neighborhood. Consequently, this neighborhood typology is associated with higher possibility of household coal use, holding all other variables constant. In other words, the Traditional neighborhood form "encourages" the use of coal.

6.3 Appliance Ownership Model

Appliance ownership directly influences household energy use. Using the survey data, we can examine household ownership of five appliances: air-conditioner (AC), refrigerator, TV, desktop computer, and solar water heater. We still use the logistic model to examine household appliance ownership choice (see Equation (10), Section 3.3). For each appliance, only the relevant variable vectors are included in the model.

Air Conditioning (AC) Ownership

The modeling of AC ownership is slightly different from other appliances, since in many cases households own more than one AC (see **Figure 19**). In this case, we would like to examine the likelihood of household owning 0, 1 or more than 1 AC. Since more than two nominal choices are available, the multinomial logit model is a more appropriate approach. The modeling result of AC is shown in **Table 14**.

	AC=1				AC=2+			
Variables	**Coefficient**		**Z-test**	**Odds Ratio**	**Coefficient**		**Z-test**	**Odds Ratio**
HHincome_100USD	**0.009**	***	25.277	1.009	**0.012**	***	48.056	1.012
Adult_1	ref.				ref.			
Adult_2	0.023		0.009	1.024	0.329		0.865	1.390
Adult_3+	-0.307		1.005	0.736	0.077		0.035	1.080
Kid	**0.302**	**	3.978	1.353	**0.545**	***	9.299	1.725
Elderly	-0.336		1.969	0.715	-0.121		0.201	0.886
Rental	**-1.032**	***	40.419	0.356	**-1.559**	***	48.953	0.210
Attitude_prestige	-0.118		0.499	0.888	-0.239		1.478	0.787
Attitude_saveenergy	**-0.495**	**	5.777	0.609	**-0.658**	***	7.802	0.518
LN_area	**1.051**	***	49.637	2.861	**2.798**	***	141.894	16.404
TopFloor	0.247		1.285	1.281	**0.574**	**	5.084	1.776
electric.heating	**0.578**	***	11.482	1.783	**0.434**	**	4.189	1.544
Electric_fan	**-0.113**	*	2.798	0.893	**-0.166**	**	4.691	0.847
Superblock	ref.				ref.			
Enclave	0.084		0.112	1.088	**-0.758**	***	8.334	0.468
Grid	-0.360		1.568	0.698	**-1.304**	***	17.614	0.271
Traditional	**-1.480**	***	23.683	0.228	**-4.741**	***	100.250	0.009
(Constant)	**-3.369**	***	19.958		**-11.209**	***	92.735	
No. Observations	2334							
Ownership =1	865		37.06%					
Ownership =2+	949		40.66%					
Chi Square	1531.979							

LogLikelihood(Intercept)	4942.019
Log Likelihood(Final)	3410.040
Pseudo R2	0.307

p*<0.1, p**<0.05, p***<0.01

Table 14 Multinominal Choice Model of AC ownership

The modeling result reveals a number of relevant factors associated with owning a different number of ACs. Some factors, such as income, home ownership, and household attitude, make intuitive sense and are not discussed in detail. Instead, we highlight findings of particular potential relevance to neighborhood typology:

- Household size does not affect household AC ownership. One possible explanation is that large households have many other demands to satisfy beyond AC. When the total income of the household is held constant, spending money on other purposes might bring higher utility than spending on AC.

- Having children significantly increases the possibility that a household owns ACs. This is in accordance with our hypothesis that children need more convenient living environment than adults, and Chinese parents are willing to spend money to create better living condition for their children. However, the result suggests that the presence of elderly does not affect AC ownership choice.

- Households living on the top floor of a building are more likely to own more than one AC compared to other households. This finding is in accordance with the commonly observed factor that top floor units have harsher environmental conditions compared to other floors, given direct exposure to surface solar and out-door temperature impact.

- The relationship between electric fan ownership and AC ownership suggests the two types of appliances are substitutes. The electric fan appears to be an inferior good, which means that the demand for electric fan will decrease when household income increases, given that AC provides much higher comfort level. The model supports this: households owning more electric fans are less likely to own ACs.

- Finally, we examine the relationship between neighborhood form and household AC ownership choice. All else equal, households living in the Traditional type are less likely to own 1 AC compared to Superblock households. What is more, households in the Enclaves, the Grid and the Traditional are all less likely (respectively) to buy extra ACs (more than 1) compared to the Superblock households, as all three dummy variables are significant at 0.01 level.

The last point above suggests that the Superblock neighborhood form may "encourage" air conditioner ownership. According to the results of the model for the choice of 1 AC, the choice is mostly determined by individual household characteristics; neighborhood type makes a difference only for the Traditional. It is possible that the traditional lifestyle in this neighborhood is strongly inclined to natural ventilation rather than AC On the other hand, the neighborhood type has a strong relationship with the household's choice to own more than one AC. A plausible explanation lies in the diversity of neighborhood functions. As discussed in Chapter 4, the Superblocks have highly homogeneous residential land use with very limited shops, restaurants and entertainments. In comparison, the other three neighborhoods have more diverse functions, meaning that, for example, during the summer season, people have more choices to going out locally for entertainment and enjoying natural ventilation instead of the AC-cooled home. In this sense, the neighborhood form affects household AC ownership choice through affecting household behavior. Since the Superblocks reduce the "street life" option for residents, those residents may demand more ACs, as well as the associated electricity consumption.

One extra consideration is that the AC choice model might be a nested logit instead of multinominal logit. In a nested logit framework, the three options are not independent. The decision of owning 1 AC or owning 2 or more ACs is based upon the decision of owning AC or not, as shown below:

$$Pr(AC = 1) = Pr(AC = 1 | AC = Y) * Pr(AC = Y)$$

$$Pr(AC = 2 +) = Pr(AC = 2 + | AC = Y) * Pr(AC = Y)$$

An Independence of Irrelevant Alternative (IIA) test will tell whether the AC ownership choice fits into multinominal logit or nested logit framework. Given time constraints, this issue is not examined in the thesis.

TV, Refrigerator and Desktop Ownership

Table 15 presents the logit model for TV ownership choice, and **Table 16** presents the logit models for refrigerator and desktop ownership choice. For TV ownership, we use multinominal logit model instead of binary because a number of households own 2 or more TVs.

	TV=1				TV=2+			
Variables	**Coefficient**		**Z-test**	**Odds Ratio**	**Coefficient**		**Z-test**	**Odds Ratio**
HHincome_100USD	0.002		0.980	1.002	**0.006**	**	5.908	1.006
Adult_1	ref.				ref.			
Adult_2	**0.539**	*	3.781	1.714	**1.187**	**	5.928	3.277
Adult_3+	0.397		0.907	1.487	**1.136**	*	3.688	3.114
Elderly	**1.114**	***	16.645	3.048	**1.376**	***	20.844	3.959
Kid	-0.104		0.047	0.901	0.096		0.035	1.100
Rental	**-2.426**	***	70.438	0.088	**-3.122**	***	80.220	0.044
Attitude_prestige	**-0.469**	*	3.187	0.625	-0.358		1.496	0.699
Attitude_saveenergy	-0.214		0.536	0.808	**-0.551**	*	2.934	0.576
Bedroom_1	ref.				ref.			
Bedroom_2	0.005		0.000	1.005	0.398		1.508	1.489
Bedroom_3+	0.430		1.401	1.538	**1.706**	***	16.554	5.504
(Constant)	**3.199**	***	48.252		0.134		0.044	
No. Observations	2333							
Ownership =1	1764		75.61%					
Ownership =2+	458		19.63%					
Chi Square	501.895							
Log Likelihood(Intercept)	2327.903							
Log Likelihood(Final)	1826.008							
Pseudo R2	0.159							

p*<0.1, p**<0.05, p***<0.01

Table 15 Multinominal Choice Model of TV ownership

	Refrigerator				Desktop			
Variables	**Coefficient**		**Z-test**	**Odds Ratio**	**Coefficient**		**Z-test**	**Odds Ratio**
HHincome_100USD	-0.002		0.980	1.002	**0.012**	***	114.528	1.012
Adult_1	ref.				ref.			
Adult_2	**0.601**	**	6.286	0.548	0.140		0.532	0.870
Adult_3+	**0.729**	**	5.436	0.483	0.269		1.271	0.764

Kid	**0.691**	***	17.295	0.501	**-0.412**	***	5.075	0.663
Elderly	0.048		0.026	0.954	**-0.904**	**	65.501	2.469
Rental	**-3.113**	***	385.077	22.487	**-0.820**	***	48.671	0.440
Attitude_prestige	-0.082		0.171	1.086	**0.233**	*	3.416	0.792
Attitude_saveenergy	-0.246		1.294	1.279	**-0.312**	**	4.538	0.732
(Constant)	**-1.706**	***	29.547		-0.042		0.033	
No. Observations	2340				2331			
Ownership =Yes	1982		84.7%		1620		69.5%	
Chi Square	806.689				419.008			
Log Likelihood(Intercept)	1511.387				1803.735			
Log Likelihood(Final)	704.698				1384.728			
Pseudo R2	0.403				0.146			

p*<0.1, p**<0.05, p***<0.01

Table 16 Binary Logit Choice Model of Refrigerator and Desktop

Most results of the model are in accordance with our hypotheses. Households with higher income are more likely to own appliances, since additional income directly expands the budget constraint. Larger households also have higher probability of owning appliances, because more people, all else equal, increases the likely demand for appliance functionality, thus increasing the utility gained per unit dollar input for purchasing the appliance. The presence of children increases the possibility of a household owning appliances, again reflecting Chinese households' willingness to spend money to increase their children's living standard. On the other hand, the presence of elderly negatively impacts the desktop ownership choice, perhaps for the reason that older people rely less on computer technology for work and entertainment.

The impact of attitudes is significant as well. Households caring more about energy saving are less likely to own extra TVs and desktops, and households inclined towards prestige are likely to own desktops. Again, this variance suggests a life style difference, either frugal or extravagant.

The home physical attributes only affect the ownership of TVs. Intuitively, the more rooms in a household, the more TVs. The model suggests that households living in larger homes with more bedrooms are more likely to own more than 2 TVs.

In general, individual household characteristics dominate the ownership of the TVs, refrigerators and desktops. However, the relatively modest explanatory power of these models should be noted, with the Pseudo R^2 of TV model and desktop model smaller than 0.20. Obviously, many other variables outside the scope of our model account for these choices.

Solar Water Heater Ownership

Finally, **Table 17** presents the standard binominal logistic choice model results for solar water heater ownership.

Variables	Coefficient		Z-test	Sig.	Odds Ratio
HHincome_100USD	**0.003**	***	14.553	0.000	1.003
Adult_1	ref.				
Adult_2	0.071		0.059	0.809	1.074
Adult_3+	0.080		0.066	0.798	1.083
Rental	**-1.063**	***	30.179	0.000	0.345
Attitude_saveenergy	-0.217		1.766	0.184	0.805
TopFloor	**0.683**	***	14.494	0.000	1.981
Superblock	ref.				
Eclave	**2.444**	***	136.847	0.000	11.513
Grid	**1.792**	***	45.738	0.000	6.002
Traditional	**1.594**	***	26.577	0.000	4.923
(Constant)	**-3.610**	***	93.570	0.000	
No. Observations	2276				
Ownership=Yes	343		15.1%		
Chi Square	249.600				
Log Likelyhood(Intercept)	1289.749				
Log Likelyhood(Final)	1040.150				
Pseudo R2	0.129				

p*<0.1, p**<0.05, p***<0.01

Table 17 Binary Logit Model of Solar Water Heater Ownership

The model displays relatively low goodness of fit, as measured by the rho square value of 0.129. Among the socio-demographic and attitude variables introduced into the model, only home ownership is significant. Renters seem more unlikely to install solar water heaters, similar to the finding for coal choice, ACs, and other appliances, indicating again perhaps an unwillingness to invest in items which may be difficult to install, difficult or impossible to uninstall (in the case of moving) and/or prohibited by landlords. The income effect is significant in the model. It is possible that higher income households tend to have lower discount rates meaning they would more greatly value longer-term energy savings and be more willing to invest now for those savings in the future. Household size has no significant impact, going against our hypothesis that larger households increase demand for water heating and thus the likelihood of considering operational cost savings through using solar water heaters. Surprisingly, household attitude towards saving energy also shows no significant impact, indicating that the purchase decision of solar water heaters might not be based upon energy saving or cost saving rationale.

Characteristics associated with the neighborhood form suggest that physical constraints play a meaningful role in solar water heater ownership. Households living in top floor units are much more likely to own solar water heaters. Given the prevailing technique, solar water heaters can only be installed on building rooftops, increasing the likelihood that households living on top floors have the installation option. The three neighborhood typology dummies are all significant with positive coefficient signs, suggesting that households in Enclave, Grid and Traditional are more likely, respectively, to own solar water heaters than Superblock households. A likely reason is that the Superblocks have a high presence of high-rise buildings, which enable only households living on the top two or three floors to install solar water heaters. Meanwhile, according to the odds ratio, the enclave households are most likely to own solar water heater, followed by the Grid and the Traditional. A possible explanation is that the Enclaves have more organized building layout with moderate building-to-building distance, thus are more "solar friendly".

6.4 Energy Consumption and GHG Emission Model by Energy Source

We now specify and estimate models of estimated total household energy consumption and GHG emissions for the three energy sources, electricity, coal and gas. The basic models take the linear form, as introduced in the methodology section (Equation (8) and (9), Section 3.3)

Electricity

1 Stage OLS Model

I first specify and estimate an OLS regression model of electricity consumption and associated GHG emission. **Table 18** shows the results.

	Electricity Energy Consumption Model									**GHG Emission Model**		
	Household Basic Model			**Plus Appliance Ownership**			**Plus Neighborhood Typology**			**LN (kg CO2)**		
Variables	**Coeff.**		**t**	**Coeff.**		**t**	**Coeff.**		**t**	**Coeff.**		**t**
Socio-demographics												
HHincome_100USD	**0.001**	***	5.205	**0.001**	***	2.920	**0.001**	***	3.095	**0.001**	***	3.095
Adult_1	ref.			ref.								
Adult_2	**0.175**	***	3.493	**0.151**	***	3.018	**0.149**	***	2.976	**0.149**	***	2.976
Adult_3+	**0.253**	***	4.217	**0.228**	***	3.805	**0.224**	***	3.732	**0.224**	***	3.732
Kid	**0.152**	***	5.415	**0.090**	***	3.205	**0.087**	***	3.079	**0.087**	***	3.079
Elderly	0.015		0.357	0.029		0.685	0.025		0.589	0.025		0.589
Rental	**-0.118**	***	-3.355	0.060		1.550	0.046		1.167	0.046		1.167
Attitudes												
Attitude_prestige	0.008		0.260	0.017		0.563	0.013		0.426	0.013		0.426
Attitude_saveenergy	**-0.108**	***	-3.266	**-0.077**	**	-2.393	**-0.078**	**	-2.421	**-0.078**	**	-2.421
Home Physical												
LN_area	**0.563**	***	23.766	**0.429**	***	16.622	**0.446**	***	16.041	**0.446**	***	16.041
TopFloor	0.023		0.575	0.035		0.918	0.031		0.815	0.031		0.815
Heating Method												
Electric.heating	**0.125**	***	3.918	**0.124**	***	3.896	**0.117**	***	3.627	**0.117**	***	3.627
Appliance Ownership												
AC=0				ref.			ref.			ref.		
AC=1				**0.170**	***	4.613	**0.194**	***	5.117	**0.194**	***	5.117
AC>=2				**0.215**	***	5.104	**0.247**	***	5.615	**0.247**	***	5.615

Fridge				**0.288**	***	6.364	**0.302**	***	6.605	**0.302**	***	6.605
TV=0				ref.			ref.			ref.		
TV=1				0.082		1.375	0.071		1.187	0.071		1.187
TV >=2				**0.231**	***	3.473	**0.210**	***	3.142	**0.210**	***	3.142
Desktop				**0.122**	***	4.201	**0.129**	***	4.424	**0.129**	***	4.424
Solar Water Heater				**-0.075**	***	-2.311	**-0.081**	**	-2.371	**-0.081**	**	-2.371
Neighborhood Typology												
Superblock							ref.			ref.		
Enclave							0.022		0.630	0.022		0.630
Grid							0.054		1.175	0.054		1.175
Traditional							**0.138**	**	2.561	**0.138**	**	2.561
(Constant)	**7.316**	***	64.169	**7.350**	***	58.659	**7.229**	***	50.868	**4.871**	***	34.274
No. Observations	2341			2262			2262			2261		
F Value	134.924			94.398			81.471			85.893		
R2	0.386			0.426			0.428			0.429		

p*<0.1, p**<0.05, p***<0.01

Table 18 Electricity Energy Consumption and GHG Emission Model

Most of the results are in accordance with our hypotheses. Higher income, larger household size, presence of children, larger home construction area, and more appliances contribute to higher electricity energy consumption and GHG emissions. Strong awareness towards saving energy has an inverse effect, reducing electricity energy consumption and GHG emission. Beyond these intuitive relationships, some other findings warrant more in-depth discussion:

- Home ownership impact is significant in the household basic model, where rental status reduces electricity consumption. But once appliance ownership is controlled for, the home ownership impact is no longer significant. This finding suggests that home ownership affects electricity consumption through appliance ownership: renters use less electricity than home owners merely because renters tend to own fewer appliances, as indicated in the previous section.

- The top-floor dummy is not significant in the electricity model, because the top-floor exerts its impact on household choice of AC ownership. After controlling for the AC2+ category, there is no further increase in electricity use.

- Whether a household uses electricity as the space heating energy source has significant impact on electricity consumption. This finding makes intuitive sense, but the scale is worth examining. The coefficient of the dummy variable is 0.117 in the final model, indicating that households using electricity heating consume only 12.4% more electricity energy than households using centralized heating or coal as the heating source. This scale is relatively small. In a simplified calculation, we assume two average superblock households with the same socio-demographics (2 adult with 1 kid, no elderly, 10,000USD annual income, owner-occupied, 100 square meter home), attitudes and appliance ownership, but one using centralized heating and the other using electric heating. The electricity energy consumption would be around 29,600MJ for electricity heating user and 26,500MJ for centralized heating user. When adding in the centralized heating energy consumption, the latter will be 61,500MJ. If gas consumption is equal for the two households (8,000MJ), the total energy consumption of centralized heating household would be 80% higher than the electricity heating household. This finding is very meaningful, suggesting that electricity heating is much less energy intensive compared to centralized heating. The rationale is again behavior-related: electricity heating is more flexible. Households can easily adjust usage according to timely needs and the energy bill. Moreover, they can choose to heat only a limited amount of space, such as the bedrooms, rather than heating the whole home. But it is also notable that convenience level is not controlled in the model. Electricity heating may not be as convenient as centralized heating, especially under harsh winter climate.

- Finally, holding all other variables equal, we find only a significant effect for the Traditional Neighborhood. That is, households in Traditional neighborhoods will consume, on average, almost 15% more electricity than households from the other neighborhood types. The most plausible explanation lies in the building type difference. As confirmed by various studies both from empirical perspective and simulation perspective, low-rise detached or semi-detached buildings are less energy efficient compared to multifamily mid-rise and high-rise buildings, considering the shape coefficient (surface-volume ratio) impact. Buildings in the Traditional neighborhood are predominantly single detached, thus they are expected to be more electricity-consuming with regard to space heating and cooling. Meanwhile, since the building density is very high in the Traditional neighborhood with no organized building layout, the insufficient gain of daylight might cause extra consumption of in-home lighting thus increase electricity consumption.

In the GHG emission model, the coefficients and t-values are all identical to those in the electricity consumption model. The reason is that the dependent variables in the two models take the logarithmic form, and the GHG emissions are directly converted from electricity consumption by multiplying a constant conversion factor. Under such setting, the only difference between the two models is the constant (intercept), while all other relationship between variables will be the same.

2-Stage OLS Model

As outlined in Chapter 3, household energy consumption involves discrete-continuous choices. The purchase choice of appliances is discrete, while the consumption choice, given a set of appliance ownership is continuous. Endogeneity exists mainly due to omitted variables which affect both appliance use and appliance ownership choice. To address the issue, we use the 2-Stage approach, as introduced in the methodology section (Equation (12) and (13), Section 3.3).

One critical prerequisite of two-step modeling is to identify valid instrumental variables. Theoretically, the instrumental variable in our model should affect appliance ownership, but be unrelated with the error term in the original model. Unfortunately, we are not able to find very satisfactory instrumental variables given data limitations. The survey did not cover enough information about household preference, behavior and attitude to instrument appliance ownership. The mitigation approach is to use some variables that have been tested to be insignificant in the 1-stage model, such as the home ownership dummy and the top-floor dummy, as instrumental variables.

The two-step approach uses the appliance ownership probability estimated by the logistic choice models presented in the last section to replace the observed ownership variables in the reduced form electricity consumption model (Equation (12) Section3.3). The result is shown in **Table 19**.

	1 Stage OLS				**2 Stage OLS**		
Variables	**Coefficient**		**t-value**	**VIF**	**Coefficient**	**t-value**	**VIF**
Houshold Basics							
Income_100USD	**0.001**	***	3.125	1.443	0.001	1.473	6.022
Adult_1	ref.				ref.		

Adult_2	**0.145**	***	2.908	4.325	**0.167**	***	2.908	5.565
Adult_3+	**0.236**	***	4.261	4.691	**0.263**	***	4.127	6.016
Kid	**0.087**	***	3.133	1.283	**0.108**	**	2.208	3.890
Attitude_saveenergy	**-0.083**	***	-2.681	1.022	**-0.089**	**	-2.557	1.222
LN_area	**0.442**	***	16.175	2.178	**0.709**	***	13.951	7.238
Electric.heating	**0.120**	***	3.747	1.166	**0.150**	***	4.121	1.476
Appliance Ownership								
AC=0	ref.							
AC=1	**0.191**	***	5.051	2.545				
AC>=2	**0.244**	***	5.564	3.552				
Fridge	**0.284**	***	6.555	1.830				
TV=0								
TV=1	0.059		0.999	4.949				
TV >=2	**0.198**	***	2.998	5.314				
Desktop	**0.128**	***	4.401	1.355				
Solar Water Heater	**-0.081**	**	-2.376	1.140				
Logit Estimation								
P_AC=1					**0.668**	***	4.246	6.787
P_AC2+					**1.086**	***	4.311	32.874
P_Fridge					0.017		0.081	17.273
P_TV1					-0.181		-1.021	3.191
P_TV2+					-0.299		-0.600	13.876
P_Desktop					-0.442		-1.707	17.800
P_Solar WH					**-1.169**	***	-3.928	9.068
Neighborhood Typology								
Superblock	ref.				ref.			
Enclave	0.026		0.746	2.260	**-0.531**	***	-5.061	19.716
Grid	0.058		1.274	1.523	**-0.465**	***	-5.024	6.123
Traditional	**0.151**	***	2.822	2.392	**-0.620**	***	-4.917	12.840
(Constant)	**7.293**	***	56.132		**7.854**	***	21.898	
No. Observations	2262				2262			
F Value	100.556				89.895			
R2	0.428				0.393			

p*<0.1, p**<0.05, p***<0.01

Table 19 2-Stage OLS Model of Electricity Energy Consumption

The model does not provide satisfactory results. Four out of the seven appliance ownership dummies show no significant impact, while the remaining three have unreasonably high coefficient values. The major causes are poor instruments and subsequent multicollinearity. The logit models of appliance ownership have relatively low Pseudo R2, suggesting limited explanation power of the variances. The estimated ownership probability dummies in the 2-stage model have high measures of collinearity (VIF values), which is not surprising because most variables used to estimate appliance ownership exist in the OLS model. Given data limitations, we are unable to find effective instruments for the 2-stage approach. Accordingly, in the following analysis we continue to use the 1-stage approach, even though the 2-stage approach is theoretically more justifiable.

Coal

The coal energy consumption and GHG emissions models use the same OLS regression method as the electricity part. The result is shown in **Table 20.** In this model I use the building type dummy instead of the neighborhood typology dummies, since building type is the factor most likely affecting household coal consumption from the thermal perspective.

	Coal Energy Consumption Model				**Coal GHG Emission Model**			
Variables	**Coefficient**		**t-value**	**Sig.**	**Coefficient**		**t-value**	**Sig.**
Socio-demographics								
Income_100USD	0.000		-0.175	0.861	0.000		-0.175	0.861
Adult_1	ref.				ref.			
Adult_2	**0.242**	*	1.875	0.062	**0.242**	*	1.875	0.062
Adult_3+	**0.320**	**	2.060	0.040	**0.320**	**	2.060	0.040
Kid	0.044		0.632	0.527	0.044		0.632	0.527
Elderly	0.147		1.444	0.150	0.147		1.444	0.150
Rental	**-0.349**	***	-3.844	0.000	**-0.349**	***	-3.844	0.000
Attitude_prestige	0.051		0.700	0.485	0.051		0.700	0.485
Attitude_saveenergy	-0.059		-0.694	0.488	-0.059		-0.694	0.488
LN_area	**0.277**	***	4.992	0.000	**0.277**	***	4.992	0.000
Centralized_heating	**-0.777**	***	-3.690	0.000	**-0.777**	***	-3.690	0.000
Low_rise	**0.164**	**	2.323	0.021	**0.164**	**	2.323	0.021
(Constant)	**9.013**	***	34.404	0.000	**9.013**	***	34.404	0.000
No. Observations	419				419			
F Value	11.813				11.813			
R2	0.221				0.221			

p*<0.1, p**<0.05, p***<0.01

Table 20 Coal Energy Consumption and GHG Emission

According to the model results, the impact of household size and home construction area is significant, which makes intuitive sense. Also, if a household uses centralized heating, the consumption of coal will dramatically decrease since these two energy sources are substitutes. In addition, the following findings are important:

- The income effect of coal consumption is not significant, indicating that the consumption is rigid: households with higher income do not consume more coal, holding other variables equal. The major reason is that coal is mainly used for space heating, the demand for which is highly rigid in regions with harsh winter.

- The presence of children and elderly does not affect coal energy consumption, against our hypothesis that children and elderly require warmer in-home temperature. The attitudes have no significant impact confirmed either, again indicating that coal consumption is rigid demand with low elasticity.
- Households in low-rise buildings consume more coal, in accordance with the hypothesis that low-rise buildings are less thermally energy-efficient than mid-rise and high-rise buildings, given higher ratio of surface exposure to out-door air. Holding all else equal, low-rise building households will consume 18% more than other households. The finding again supports the neighborhood form impact on energy consumption, since most low-rise detached buildings exist in the Traditional neighborhood.

Notably, selection bias is an econometric issue that should be acknowledged in the current model. The model uses the 419 households that use coal as the sample; this approach over-represents the households that have already self-selected to be coal users. To address the issue, the Heckman Correction should be applied by incorporating a predicted probability of coal use as an additional explanatory variable into the model. However, due to time constraints, the correction approach is not conducted in this thesis.

Gas

Using the same method as electricity and coal, the gas energy consumption and GHG emission models are constructed, as shown in **Table 21.** The factors impacting gas use are relatively simple compared to the other energy sources, and fewer variables are included in the model.

	Gas Energy Consumption Model				Gas GHG Emission Model			
Variables	**Coefficient**		**t-value**	**Sig.**	**Coefficient**		**t-value**	**Sig.**
Gas Source								
Natural Gas	**0.211**	***	4.818	0.000	**0.093**	**	2.131	0.033
Coal Gas	-0.030		-0.550	0.582	**-0.382**	***	-6.904	0.000
LPG	ref.				ref.			
Socio-demographics								
Income_100USD	**0.000**	*	1.920	0.055	**0.000**	*	1.920	0.055
Adult_1	ref.				ref.			
Adult_2	-0.055		-0.605	0.545	-0.055		-0.605	0.545
Adult_3+	-0.009		-0.088	0.930	-0.009		-0.088	0.930
Kid	**0.082**	*	1.919	0.055	**0.082**	*	1.919	0.055
Elderly	0.002		0.040	0.968	0.002		0.040	0.968
Rental	-0.077		-1.454	0.146	-0.077		-1.454	0.146
Attitudes								
Attitude 27_prestige	0.053		1.185	0.236	0.053		1.185	0.236
Attitude 30_saveenergy	0.055		1.095	0.274	0.055		1.095	0.274
Appliance								
Gas Water Heater	**0.132**	*	1.777	0.076	0.132		1.777	0.076
(Constant)	**8.401**	***	82.741	0.000	**5.638**	***	55.528	0.000
No. Observations	1839				1839			
F Value	6.943				11.236			
R2	0.034				0.058			

p*<0.1, p**<0.05, p***<0.01

Table 21 Gas Energy Consumption and GHG Emission

The models have relatively low explanatory power, as indicated by the R squares (0.034, 0.058). This may in large part be a data quality problem. First, the monthly consumption data is self-reported rather than obtained from the utility company, thus the accuracy is low. Furthermore, since gas expenditures are much lower than electricity (see **Figure**

22), households may care less about it, so many respondents may not be sure about how much gas they consume; some of them even do not know what type of gas they are using. Second, the data entry involves a technical mistake. Households using LPG have two quantification methods: one is the number of steel bottles (the LPG container) consumed, and the other is the number of liters consumed. But the data entry did not specify the quantification unit, thus the result for LPG is by no means reliable. Given these drawbacks, the modeling result does not provide valuable insights, although a few hypotheses have been tested and supported. Further analysis will rely on data with higher quality.

Notably, the household gas coverage in our survey (81.5%) is much lower than the number announced by the government (97.8%). As mentioned earlier, many households are unsure about the type and amount of gas they consume so the gas category is often left blank. Self-selection bias might also exist in the model, and further improvement of the model relies on extra data input.

6.5 Total Energy Consumption and GHG Emission Model

Finally, a full model covering electricity, coal and gas energy consumption is constructed, together with the total GHG emission model. Note that these models DO NOT include centralized heating, for which no empirical data is applicable given the fact that centralized heating is not metered in Chinese households. The models are shown in **Table 22**.

	Total Energy Consumption Model				Total GHG Emission Model			
Variables	**Coefficient**		**t-value**	**Sig.**	**Coefficient**		**t-value**	**Sig.**
Energy Sources								
Use Gas	**0.250**	***	8.461	0.000	**0.157**	***	5.237	0.000
Use Coal	**0.897**	***	25.850	0.000	**0.965**	***	27.317	0.000
Use Centralized Heating	**-0.132**	***	-4.279	0.000	**-0.147**	***	-4.663	0.000
Socio-demographics								
Income_100USD	**0.001**	***	3.844	0.000	**0.001**	***	3.921	0.000
Adult_1	ref.				ref.			
Adult_2	**0.151**	***	3.356	0.001	**0.146**	***	3.177	0.002
Adult_3+	**0.213**	***	3.942	0.000	**0.210**	***	3.819	0.000
Kid	**0.094**	***	3.692	0.000	**0.093**	***	3.589	0.000
Elderly	0.017		0.462	0.644	0.016		0.422	0.673
Rent	0.023		0.633	0.527	0.022		0.603	0.546
Attitudes								
Attitude_prestige	0.029		1.076	0.282	0.024		0.867	0.386
Attitude_saveenergy	**-0.055**	*	-1.892	0.059	**-0.062**	**	-2.093	0.036
Home Physical								
LN_area	**0.396**	***	15.821	0.000	**0.402**	***	15.789	0.000
TopFloor	0.016		0.471	0.638	0.014		0.411	0.681
Appliance Ownership								
AC=0	Ref.				Ref.			
AC=1	**0.153**	***	4.507	0.000	**0.163**	***	4.704	0.000
AC>=2	**0.210**	***	5.267	0.000	**0.228**	***	5.614	0.000
Fridge	**0.230**	***	5.537	0.000	**0.235**	***	5.551	0.000
TV=0	Ref.				Ref.			
TV=1	0.115		2.128	0.033	0.109		1.993	0.046
TV >=2	**0.216**	***	3.594	0.000	**0.218**	***	3.570	0.000
Desktop	**0.087**	***	3.325	0.001	**0.094**	***	3.531	0.000
Solar Water Heater	**-0.071**	**	-2.304	0.021	**-0.073**	***	-2.320	0.020

Neighborhood Typology								
Superblock	Ref.				Ref.			
Enclave	-0.008		-0.232	0.817	-0.017		-0.509	0.611
Grid	0.018		0.422	0.673	0.015		0.359	0.719
Traditional	-0.017		-0.332	0.740	-0.019		-0.359	0.720
(Constant)	**7.643**	***	59.957	0.000	**5.256**	***	40.493	0.000
No. Observations	2262				2262			
F Value	127.205				126.560			
R2	0.562				0.560			

p*<0.1, p**<0.05, p***<0.01

Table 22 Total Energy Consumption and GHG Emission Model

In general, the model results are in accordance with the sub-models for individual energy sources. Since many similar findings have been identified and discussed in the previous section, the analysis in this section will only focus the new insights. Households using coal consume about 140% more energy than non-coal users. For centralized heating users, the total remaining energy consumption via electricity, and gas is 14% less.

The neighborhood typology dummies show no significant impact in this model, mainly because the neighborhood form impact has been implicitly contained in the energy source variables and appliance ownership variables. After taking these impacts into account, there is no extra effect on total energy consumption.

The coefficients in the GHG emission model are similar to those in the energy consumption model. The emission signs and the significance level are all the same, so no further interpretation is repeated.

Again, exogeneity exists in the model, and I tried the 2-stage approach by instrumenting the relevant choices such as coal and appliances. However, the problem of poor instruments and serious multicollinearity still exist, as identified in our attempt to modeling electricity energy consumption through the 2-stage approach. Improvement of the current model will require better data.

Finally, it should be emphasized again that the two "total models" above do not cover centralized heating. When using the model to estimate household energy consumption or GHG emission, the centralized heating energy consumption or GHG emission should be captured and added into the model estimation, if a household uses centralized heating.

6.6 Summary

In this chapter, we examined the household energy source choice, appliance ownership choice, and energy consumption and GHG emission of electricity, gas and coal. The models developed have moderate explanatory power, with R^2 or pseudo R^2 ranging from 0.20 to 0.60. The gas model does not produce good results, likely due to the data quality problem.

Most of the findings are in accordance with our hypotheses. In general, the impact of socio-demographics, household attitudes and home physical attributes is significant in determining household energy source choice, appliance ownership choices, and the energy usage upon the choices, with a few exceptions such as the presence of elderly and the attitude of prestige preference. The neighborhood form impact is examined through building type dummies and neighborhood typology dummies. The major finding is that the Traditional neighborhood type is associated with higher possibility of choosing coal as the energy source, and higher consumption of both electricity and coal, all else equal. Compared to the Superblock, the other three neighborhood types have lower demand for air conditioners. We also deducted from the solar water heater model that the Enclave and the Grid are more suitable for the utilization of solar energy.

The income elasticity of different energy sources is of interest. The coefficient of per capita income in the electricity energy consumption model is 0.0005, suggesting that electricity consumption will increase 0.05% per $100 increase in household income. Under current average income level (11,000USD), doubling the household income will only result in 5.5% increase in electricity consumption, when other variables are held constant. For coal energy consumption, the income effect is not significant at all, suggesting even lower elasticity. According to these findings, the urban household energy demand in China is rigid with regard to income. Note, however, that this value ignores the impact of income on appliance ownership. The real picture can only be illuminated by a system of models including both ownership and use.

To solve the endogeneity problem, we attempted the 2-stage approach. But, due to poor instruments and multicollinearity, the modeling result is not satisfactory. The fundamental limitation is again data availability, since we are unable to find very effective instrumental variables.

Chapter 7: Neighborhood Common Area Energy Consumption and GHG Emission Pattern

7.1 Overview

Common area energy consumption refers to the energy consumed outside people's homes to maintain the functional operation of buildings and neighborhood public spaces. It consists of the following components: water pumps, elevators, lighting, access security, underground parking, and others (landscape, contingencies, etc.). The energy source for common area consumption is predominantly electricity, although some neighborhoods also have space heating for in-building common area.

Common area energy consumption plays an important role in the modern residential sector of China, given the fact that gated neighborhoods have become the mainstream in urban residential development. Under such settings, each neighborhood is an independent functional unit, within which common area energy is consumed purely to serve neighborhood residents' needs. The energy bill is paid collectively by households of the neighborhood, averaged either on a per household basis or a constructed-area basis.

Neighborhood physical form to a large extent determines the "rigid demand" of common area energy consumption, considering the fundamental elements such as building height, density, neighborhood size and landscaping. This chapter develops a framework to estimate neighborhood common area energy consumption under current data limitations, utilizing methods and information from building codes, engineering manuals and local regulations. Using this framework, I calculate the common area energy consumption and associated GHG emissions of the nine sample neighborhoods. I then identify and discuss the factors influencing common area energy consumption. Finally, I compare in-home consumption and common-area consumption to demonstrate the relative importance of each, with respect to total energy use.

7.2 The Estimation Method

Framework Outline

The estimation framework is developed to mitigate the impact of data limitations in the Chinese context. Normally, the neighborhood property management companies are in charge of common area energy use and the energy fee collection. However, getting information from them has been proved extremely difficult. First, the companies were reluctant to provide information because they have no incentive to do so. Second, the companies' record does not specify the consumption of different end uses such as elevator, pump and lighting. Given these limitations, I focused on each energy end use to come up with an estimate of neighborhood-level common area energy consumption.

As discussed before, common area energy consumption consists of two parts: in-building and out-of-building. For the in-building part, consumption will vary across building types, as represented by different heights, household densities, and device installation such as elevators and lights. The out-of-building part is less complex, simply depending on the number of devices, the power capacity, and the usage frequency. Accordingly, the estimation framework takes the following steps:

Step 1: define prototype buildings in each neighborhood
Step 2: calculate in-building common area energy consumption for the prototype buildings
Step 3: extrapolate the prototype consumption pattern to the whole neighborhood based on the share of different building prototypes
Step 4: calculate out-of-building common area energy consumption based on neighborhood-level physical attributes
Step 5: combine in-building and out-of-building energy consumption to develop neighborhood-level estimates.

Categories and Assumptions

The estimation covers five categories: water pumps, elevators, lighting, access security, and underground parking. Admittedly, other "common" end uses consume energy, such as landscape (fountains, etc.), community facilities, and common area heating. But given the data limitations in our analysis, it is impossible to determine whether these end uses exist in the sample nine neighborhoods. To avoid arbitrariness, these uses are not included in the estimation.

The key underlying assumptions to our calculations are as follows:

- Households are assumed to be of equal size (3 persons per household)
- The behavior related variables, such as annual water consumption and going-out frequency, are equal for all individuals
- The device installations, such as pumps, elevators and lights, meet all related building and neighborhood design standards and regulations
- The water supply system is roof water tank style for all buildings, with water pumps installed in each building
- Buildings of 7 stories or higher have elevators. Buildings of 12 stories or above have 2 elevators per building unit[23] (4-6 households per floor), according to Design Code for Residential Buildings(2003[24])
- Lighting system controls are applied in all buildings, with light bulb wattage assumed to be equal in all neighborhoods
- The power and working hours of out-of-building lighting are equal in all neighborhoods
- All mid-rise and high-rise buildings (4 stories plus) have building access security systems
- Underground parking is operated 24 hours per day, according to common practice in China

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[23] Building unit: a residential building can consist of 2-6 `building units, each with its own entrance, stairs and elevators. Similar to the row houses in U.S., but each "house" is mid or high rise and multi-family.

[24] China Department of Construction, Design Code for Residential Buildings GB50096-1999, 2003

The Equations

The basic equation for calculating the neighborhood electricity energy consumption (KWH) is as follows:

(19) $EC = \sum_{i=1}^{n} P_i * f_i * t_i * POP_i$

Where EC is the total neighborhood electricity energy consumption, P_i is the rated power of device i, f_i is the per capita annual usage frequency of device i, t_i is the operating time per use, and POP_i is the count of population using appliance i. Based on this general format, the calculation equations for different devices can vary in detail. **Table 23** shows the calculation equations for the five end uses in our estimation framework.

Item		**Equation**	**Symbol Explanation**
Water Pump[25]		$C_p = 1.5 * \frac{P_p * N_u * N_f * N_h * N_p * Q}{q * 3{,}600}$	P_p: Power of the water pump(KW) N_u: Number of units per building N_h: Number of households per unit N_p: Number of persons per household Q: per capita annual water consumption(m3/year/person) q: designed flow volume per second(m3/sec)
Lighting	In-building Lighting	$C_{il} = \frac{N_u * N_h * N_p * E_l * T_i * N_i * P_l}{3{,}600}$ $N_i = 3 + \frac{N_u}{2} + \frac{N_f}{2}$	E_i:per capita annual lighting use frequency (use/person) T_i: lighting time per use (second/use) N_i: number of lights activated per use P_l: Power of the light bulbs (KW)
	Neighborhood Lighting	$C_{nl} = {T_n * A * \left(\frac{P_r * D_r}{d_r} + \frac{P_g * D_g}{d_g}\right)} \Big/ {1{,}000}$	T_i: light-on time per year(hour/year) A: neighborhood Size(acre) P_r: road light power(W)

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[25] Modified from: Song, 2008

			P_g: garden light power(W) D_r: road density (meter/acre) D_g: green space coverage (percent) d_r: road light density (number/meter) d_g: garden light density (number/acre)
Elevator	Working Condition	$C_{ew} = \frac{N_u * P_{ew} * T_{ew}}{3{,}600}$ $T_{ew} = \frac{N_f * N_h * N_p * E_e * H * 1.5}{V}$	P_{ew}: elevator working power(KW) T_{ew}: elevator working time(sec) E_e: per capita annual use frequency (use/person) H: building height(meter) V: elevator velocity(m/sec)
	Standby Condition	$C_{es} = \frac{N_u * P_{es} * T_{es}}{3{,}600}$ $T_{es} = T - T_{ew}$	P_{es}: elevator standby power(W) T_{ew}: elevator standby time(S) T: total seconds per year=365*24*3600
Building Access Security[26]	Working Condition	$C_{sw} = \frac{(P_{iw} * T_w + P_{ow} * T_w + P_{lw} * T_{wl}) * N_u *}{3{,}600}$	P_{iw}: in-home device working power(KW) P_{ow}: building entrance device working power(KW) P_{ls}: electric locker working power(KW) T_w: device working time per use(sec) T_{wl}: locker working time per use(sec) E_s: per capita annual use frequency(use/year)
	Standby Condition	$C_{ss} = \frac{(N_h * P_{is} + P_{os} + P_{ls} + P_v + P_{ss}) * N_u * T_s}{3{,}600}$	P_{is}: in-home device standby power (KW) P_{os}: building entrance device standby power (KW) P_{ls}: electric locker standby power (KW)

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[26] Modified from: Jia, 2006

			P_v: video monitor device power (KW) P_{ss}: electricity source power (KW) T_s: annual standby time (sec)
Underground Parking		$C_{up} = \frac{T_{up} * A_{up} * P_{up}}{1{,}000}$	T_{up}:underground garage annual operating time (hour) A_{up}: underground parking area (m2) P_{up}: per square meter garage operating power (W)

Table 23 Common Area Energy Consumption Equations

Upon the calculation result, the on-site common area electricity consumption can be converted to primary energy consumption using same equation described in Chapter 5:

(20) $E_{ec} = EC * q_e \div (1 - \beta) \div \varepsilon$

Where E_{ec} is the primary energy consumption, q_e is the conversion factor from KWH to MJ, β is electricity transmission loss rate, and ε is coal power plant conversion rate. The primary energy consumption can then be translated into GHG emission, using the emission factor of electricity production.

Note that the calculation procedure for the Grid and the Traditional is slightly adjusted. Since the Old Commercial District is not a gated neighborhood and public roads penetrate the blocks, the lighting along the public roads is not considered as purely serving neighborhood residents and thus removed from the calculation. For Zhang Village, we know that all single detached buildings are privately owned and do not have access security at all, neither is there any public green space. Thus these two end uses are excluded from the calculation.

7.3 The Results

Figure 36 shows per household, per capita and per square meter (construction area) common area energy consumption for the nine neighborhoods. According to the result, the Superblock and the Grid incur higher common area energy consumption than the other two neighborhood types. The consumption in the Traditional is very low, as is the case for Dongcang, one of the Enclaves. Notably, Sunshine 100, one of the Superblocks, consumes much more than the others, exceeding 7000 MJ per household annually.

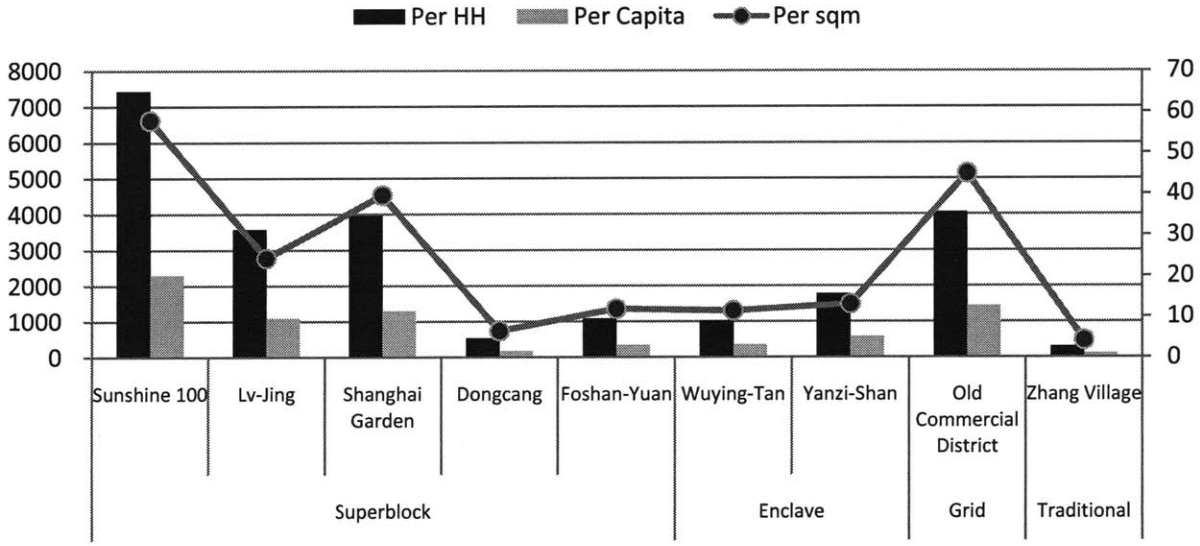


Figure 36 Annual Common Area Energy Consumption per HH, per Capita, per sqm. (MJ)

Figure 37 shows the share of each end use under the common area energy consumption category, and **Figure 38** shows the absolute value share decomposed per household consumption. According to the estimates, the water pump is the most energy-consuming end use for most neighborhoods, followed by the elevator. The share of elevator consumption is larger in the Superblocks compared to that in other neighborhoods. Only Shanghai Garden has underground parking, and the share is large in terms of both percentage and absolute value. The share of lighting is relatively higher in the Enclaves and the Traditional. Building access security has the lowest share among the five end uses.

According to **Figure 38**, the variance of lighting and access security consumption is relatively small across neighborhoods, while the consumption of water pump and elevator differs much more significantly even within the same neighborhood type. On average, Sunshine 100 households consume up to four times more pump energy and double the elevator energy than the other two Superblocks.

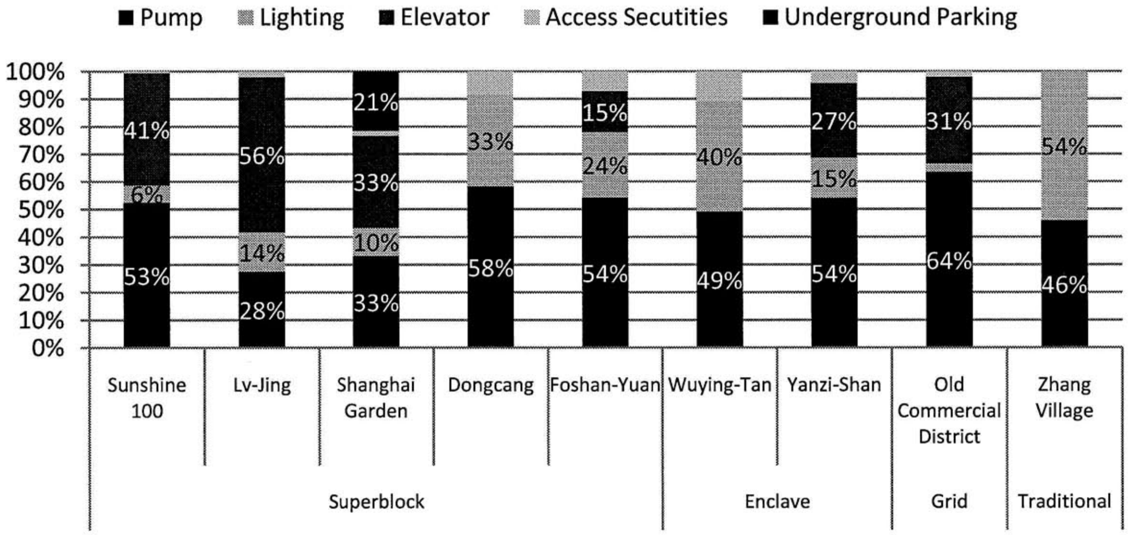


Figure 37 Energy Consumption Share by End Use

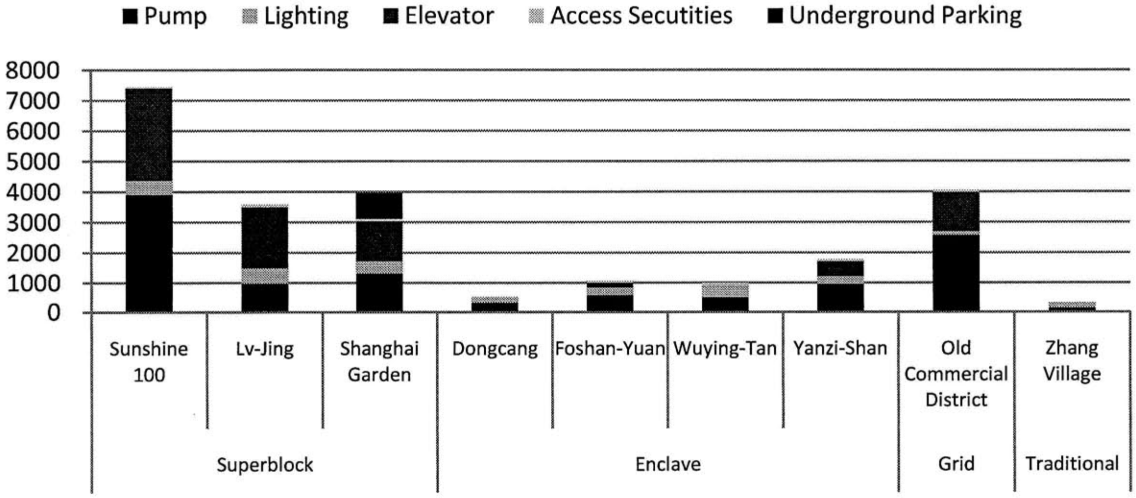


Figure 38 Absolute Value Share per HH by End Use

Table 24 shows the GHG emission associated with common area energy consumption. Since all common area energy consumption relies on electricity as the energy source, the emission factor is the same for all common area end-uses and the emission pattern across neighborhoods is the same as the consumption pattern (except for the scale and units). The Superblocks and the Grid have the highest emissions, while the Traditional have relatively little.

	Superblock			**Enclave**				**Grid**	**Traditional**
	Sunshine 100	Lv-Jing	Shanghai Garden	Dongcang	FoshanYuan	WuyingTan	YanziShan	Commercial District	Zhang Village
Total GHG Emission	6684451	443901	1740764	176601	552303	906366	2100872	3619940	178808
Per HH	703	339	375	50	102	96	168	384	28
Per Capita	218	103	123	16	33	33	54	136	10
Per sqm	5.5	2.3	3.7	0.6	1.1	1.1	1.2	4.3	0.4

Table 24 GHG Emission of Common Area Energy Consumption (kg CO2/year)

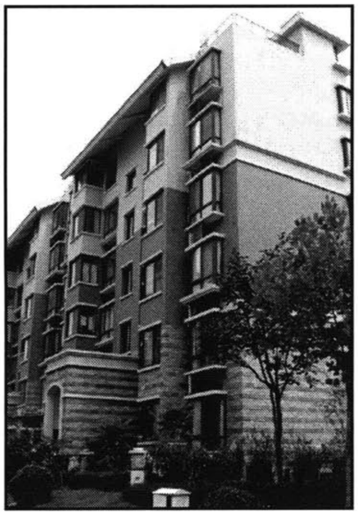
7.4 Factors Impacting Common Area Energy Consumption

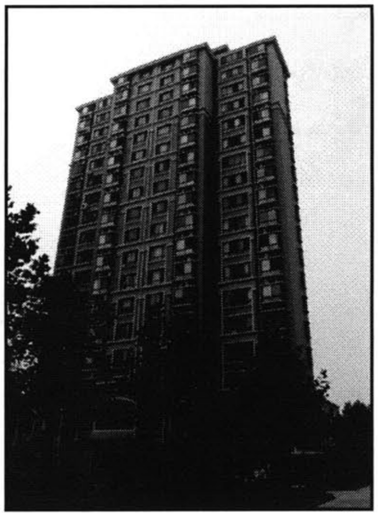
Compared to in-home consumption, the factors influencing common area energy consumption are more routine and inelastic. The physical attributes of the neighborhood, such as building height, road density and green space coverage, have more important impacts. The important influencing factors are discussed below. Note that some factors are not reflected in the estimation due to data limitations, but we are aware of their importance.

Building Height

Building height is the most important determinant of common area energy consumption, since it affects the usage pattern of water pumps and elevators, the two largest energy-consuming end uses under common area consumption category. Serving buildings of different heights, the water pumps and elevators will have different power settings. The power of high-rise building pumps can be ten times larger than that of low-rise building pumps, indicating that lifting the same amount of water will consume ten times more energy. A similar rule applies to elevators. Typical elevators serving high-rise buildings (21 stories plus) have power three times larger than those serving mid-rise buildings (7-11 stories). In low-rise buildings (6 stories less), there are no elevators at all. The difference of device settings results in large variation in estimated common area energy consumption, even within the same neighborhood where household socio-demographics are homogeneous.

To illustrate the difference, two prototype buildings are selected from Shanghai Garden, one of the superblocks, to make a comparison. Prototype A is an 18-story tower, and Prototype B is an 8-story slab. Per household common area energy consumption of the two buildings by end use is calculated in **Table 25**. As shown in the Table, per household common area energy consumption of Prototype A is two times larger than that of Prototype B. Meanwhile, the percentage share of pump energy consumption is larger in Prototype A, indicating that the consumption impact of water pump is magnified when building height increases.





	High-rise Tower	Low-rise Slab
Building Basics		
Building Height	18	8
Building Type	Tower	Slab
HH Count	144	24
# of Elevators	2	1
Elevator Power(KW)	45	15
Pump Power(KW)	17	4.5
Common Area Energy Consumption (MJ)		
Per HH	6372	2187
Per sqm	58	20
Per HH Consumption by End Use(MJ)		
Pump	3117	825
Lighting	7	11
Elevator	3224	1291
Access Security	21	60
Percentage Share by End Use		
Pump	48.9%	37.7%
Lighting	0.1%	0.5%
Elevator	50.6%	59.0%
Access Security	0.3%	2.7%
Sum	100%	100%

Table 25 Comparison: Prototype Buildings

Figure 39 shows the relationship between building height and per household common area energy consumption, based on the calculation result of a hypothetical slab building. It is obvious that common area energy consumption increases rapidly when building height increases. For buildings lower than 6 stories, the consumption is very low since elevators are not applicable. For buildings of 25 stories or higher, per household common area consumption will exceed 10,000 MJ per year, which equals about 10%-20% of estimated household in-home consumption.

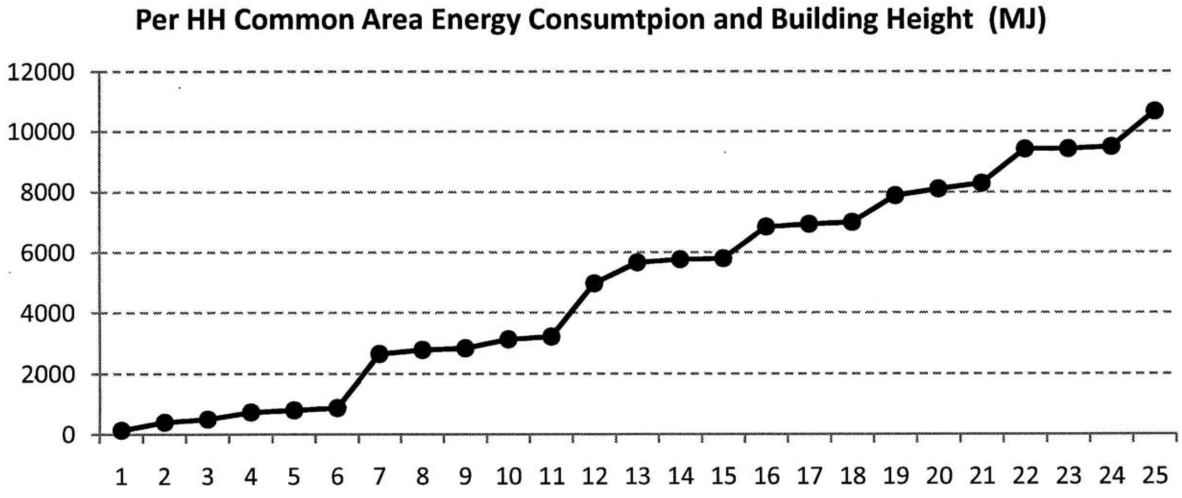


Figure 39 Relationship Between Building Height and Common Area Consumption

Parking

The way a neighborhood accommodates private cars has important impacts on common area energy consumption. Open-air parking consumes very little energy, but it requires plenty of neighborhood open space to set up the parking lots. For neighborhoods where open space is limited and the demand for parking is large, underground parking is necessary. This parking approach is highly energy-consuming, since high-luminous lighting and ventilation fans operate 24 hours a day. According to Design Code for Residential Buildings (2003[27]), the designed power intensity of underground parking is 35 W/sqm. Under such intensity, if a neighborhood has a large underground garage, the energy consumed would be large, accounting for more than 20% of total neighborhood common area consumption.

Among the nine neighborhoods in our study, only Shanghai Garden has underground parking facility, the area of which is about 1/3 of the open-air parking space. According to our calculation, the energy consumed to operate the underground parking facility takes up 21% of the neighborhood's total common area energy consumption, twice as much as lighting, and on the same magnitude as water pump and elevator consumption. Expectably, underground parking will become a more prevalent feature of Chinese residential development in the near future, considering the extreme scarcity of land and growing vehicle ownership. The associated energy consumption will increase as well. Introducing energy efficient technologies, such as sound-control lighting system, will reduce the energy intensity. However, reducing the demand for cars through transportation policy and planning may be a more fundamental solution.

Figure 40 Underground Parking Entrance, Shanghai Garden

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[27] China Department of Construction, Design Code for Residential Buildings GB50096-1999, 2003

Road Density, Green Space, Community Facilities and Landscapes

Other neighborhood physical attributes, such as road density and green space coverage, have moderate impacts through affecting lighting energy consumption. The relationship is very linear, since the consumption purely depends on the number of lights used, holding the operating time and lighting power equal. Compared to out-of-building lighting, the in-building lighting consumption is minor, since auto-off lighting control system has been widely applied and the power of in-building light bulbs is low.

The energy consumption of community facilities and landscapes is not included in the calculation due to data limitation, but its importance should not be underestimated. Most modern neighborhoods in China have gyms, swimming pools, fountains, and senior activity centers that serve the recreation needs of residents. What is more, the street level shops, restaurants, laundries and other service providers also consume energy. If these end uses purely serve the neighborhood residents rather than open to the public, their energy consumption should be counted into neighborhood common area energy consumption, since they are inherent components of neighborhood function.

Behavior

The behavior of residents have impacts on common area consumption as well, but not as significant as its impact on in-home consumption. For instance, household water consumption affects water pump energy consumption, and household going-out frequency affects the usage intensity of elevators. The civic-minded attitude is important as well, since it avoid the "tragedy of the commons" that might happen to those common area energy end uses under residents' control. But in general, the residents' usage pattern of common area devices is routine and rigid, and there is limited potential that the energy consumption will be reduced through behavior changes.

Energy Efficiency

Energy efficiency improvements can reduce common area energy consumption. One of the most important improvements is the application of auto-off lighting control systems in buildings, which reduce in-building lighting energy consumption. If the underground parking garage also uses acoustic sensors or other devices to control lighting time, energy saving as much as 50% will be achieved as well. Energy-efficient lamps are also widely used for road lighting. A 45W LED road lamp can replace a traditional 100W incandescent road lamp, saving more than 50% energy. Similarly, elevators have some efficiency opportunity to explore, although the energy-saving potential is not large (Sachs, 2005). In general, energy-efficient devices incur higher initial cost compared to normal devices and the savings are accumulated through the long run. If the cost and benefit are not fairly distributed, it is unlikely that the developers and the property management companies will be in favor of efficiency upgrades.

Convenience Level

Finally, the convenience level of neighborhood life is an implicit variable not controlled in our analysis, but its underlying impact is too important to be ignored. Higher convenience levels can only be achieved through providing more intense neighborhood services, which undoubtedly incur more energy consumption. The installation of common area devices does not follow strict regulations. In high-income neighborhoods, more elevators are installed, sometimes twice as many as those in low-income neighborhoods serving the same amount of households. As observed in Jinan, some mid-rise buildings of 7-9 stories in the Enclaves do not have elevators at all, even though it is against the Design Code for Residential Buildings. A similar case exists for lighting, community facilities and landscapes. If a neighborhood simply installs less elevators, reduces lighting coverage, and provides no recreation functions, its common area energy consumption will undoubtedly be much lower. However, this energy-saving rationale is at the cost of reducing neighborhood convenience level, which is against the demand for better living standard under the current Chinese urban context. As an overall trend, we would expect that neighborhood design will take more convenience concerns into consideration in the future, with associated increases in common area energy consumption.

7.5 The Big Picture: Comparing Common Area Energy Consumption and In-home Energy Consumption

After analyzing in-home energy consumption and common area energy consumption separately, we combine these two parts and make comparison between them. **Figure 41** shows the absolute value share of the two parts on per household basis, and **Table 22** shows the percentage share of each. Clearly, the share of in-home consumption greatly exceeds common area consumption. None of the nine neighborhoods has a common area share larger than 8%. The percentage share of common area consumption is comparatively higher in the Superblocks and the Grid, among which Sunshine 100 and the Old Commercial District have shares higher than 7%. As discussed in the previous section, neighborhoods with more presence of high-rise buildings will have larger shares of common area consumption, since the consumption of water pumps and elevators is dependent on building height. **Table 27** shows the percentage share of GHG emission from the two components. Not surprisingly, the pattern is nearly identical to that of the energy consumption share.

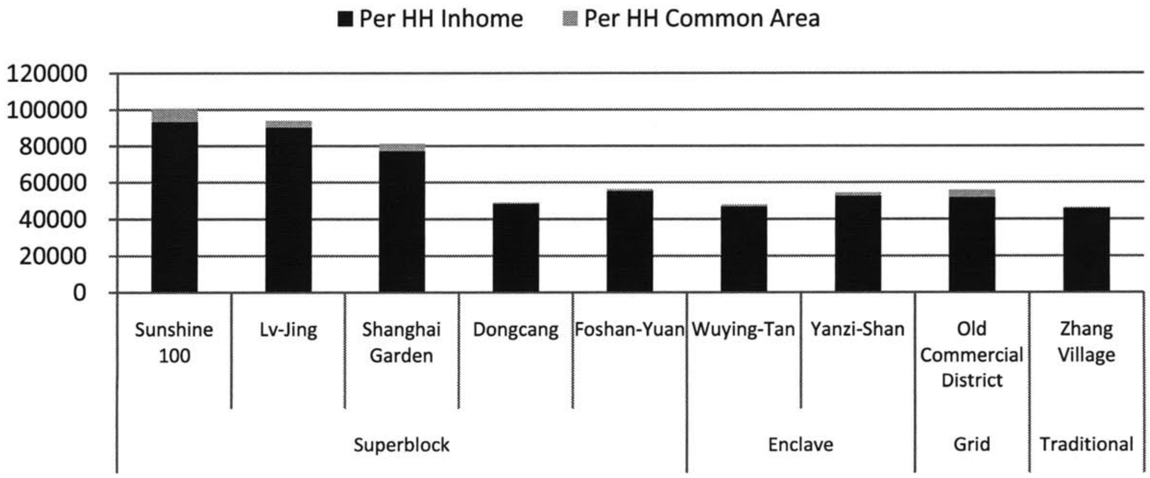


Figure 41 Absolute Value Share of In-home and Common Area Consumption by HH (MJ)

	Superblock			Enclave				Grid	Traditional
	Sunshine 100	LvJing	Shanghai Garden	Dongcang	FoshanYuan	WuyingTan	YanziShan	Commercial District	Zhang Village
In-home Share	92.6%	96.2%	95.1%	98.9%	98.1%	97.9%	96.7%	92.7%	99.4%
Common Area Share	7.4%	3.8%	4.9%	1.1%	1.9%	2.1%	3.3%	7.3%	0.6%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 26 Percentage Share of In-home and Common Area Energy Consumption

	Superblock			Enclave				Grid	Traditional
	Sunshine 100	LvJing	Shanghai Garden	Dongcang	FoshanYuan	WuyingTan	YanziShan	Commercial District	Zhang Village
In-home Share	92.2%	96.2%	94.9%	98.9%	97.8%	98.2%	96.6%	93.0%	99.4%
Common Area Share	7.8%	3.8%	5.1%	1.1%	2.2%	1.8%	3.4%	7.0%	0.6%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 27 Percentage Share of In-home and Common Area GHG Emission

To conclude, in neighborhood operational energy consumption, the in-home part is much larger than the common area part. Compared to in-home consumption, common area consumption more deterministically depends upon the physical device setting of the neighborhood, and less on resident behavior. The importance of common area consumption is relatively larger in neighborhoods with more high-rise buildings. In Traditional neighborhoods where there is no clear "common area", there is barely any common area consumption.

Chapter 8 Implication and Conclusion

8.1 Summary of Findings

In this study, I estimated residential operational energy consumption in the context of Jinan, and examined the factors influencing in-home and common area energy consumption. The major findings include:

1) In-home energy consumption accounts for the dominant proportion – 90% or higher – of neighborhood operational energy consumption. The Superblock households consume much more in-home energy compared to households in the other three types of neighborhoods. Coal is the overwhelming *primary* energy source used in the residential sector.

2) Household socio-economics and demographics, attitudes and home physical attributes influence household's choice of energy source, appliance ownership and the energy consumption pattern. The influencing factors include household income, household size, presence of children, home ownership, home construction area, and awareness towards saving energy.

3) The impact of neighborhood physical form significantly influences household energy use, but primarily through effects on fuel and in-home appliance choice which, in turn impacts final energy use. Holding all other variables equal, households living in Traditional neighborhoods are more likely to use coal as the energy source for space heating, which is associated with higher household energy use and GHG emissions. Living in Superblock neighborhoods increases the likelihood of household owning more air-conditioners, which are also associated with higher household energy use and GHGs. On the other hand, living in Enclave and Grid neighborhoods increases the likelihood of a household owning solar water heaters, which is associated with lower household energy use. Holding all other variables equal, a household will consume more electricity and coal if it lives in Traditional neighborhoods. We detect, however, no *direct* effect of neighborhood typology on household energy use.

4) Common area energy consumption accounts for 1% to 8% of neighborhood operational energy consumption, in the form of electricity. The most energy consuming end uses are water pumps (40-50%) and elevators (30%), followed by

underground parking (10-20%), lighting (10-20%) and building access security (1-5%).

5) The most important determinant of neighborhood common area energy consumption is the building composition. High-rise buildings are associated with high pump and elevator energy consumption, thus neighborhoods with more high-rise buildings have higher common area energy consumption.

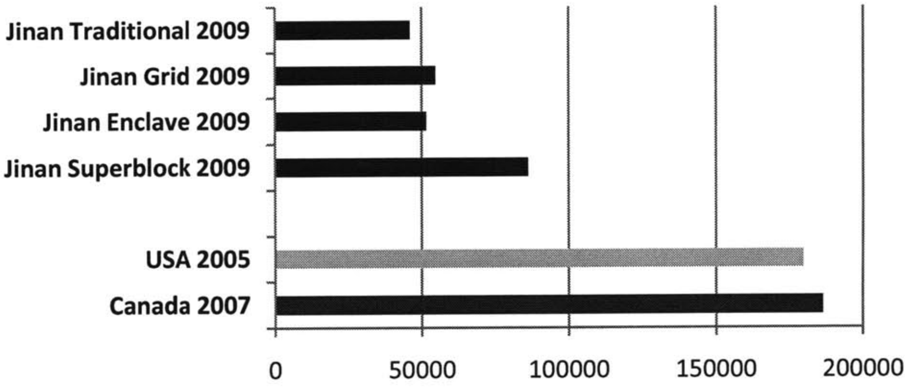
6) The GHG emissions of Jinan's residential sector ultimately come mainly from coal combustion, for electricity production, centralized heating production, or household on-site use. That is, three out of the four household energy sources rely on coal as the primary energy source, meaning that coal accounts for approximately 90% of residential end use energy consumption.

8.2 The Implications

- ***Implication one: China is catching up in residential energy intensity and GHG emission***

The survey results indicate that, the energy intensity and GHG emissions of Chinese urban residential sector has started to catch up with the industrialized countries, although the gap is still large. **Figure 42** shows the comparison of per household energy consumption in Jinan, US and Canada. Households living in Enclave and Grid neighborhoods represent, approximately, Jinan's median income population group, and they consume less than 1/3 of the US and Canadian household average. The Superblock households represent Jinan's high income population group, and they consume less than 1/2 of the US and Canadian household average. Assuming households in Jinan are roughly comparable to the average urban household in China, the gap in household energy use between China and the US has decreased considerably compared to that in 1997, when Chinese urban households consumed less than 1/4th of the US average household energy consumption (Zhang, 2004). From a GHG emissions perspective, the average Jinan household's emissions level (5.7 metric ton/year) is less than half of US average (12 metric ton/year). The smaller GHG emission gap relative to the energy consumption gap is probably because China uses much more coal, which is carbon intensive, than the U.S. Take electricity generation for example, 99% of electricity in

Jinan and 81% of electricity in overall China is produced from coal, compared to only 48% in the U.S. (International Energy Agency, 2007).



Source: U.S. EIA, Natural Resource Canada

Figure 42 Annual HH Energy Consumption Comparison with Canada and US

The decreasing residential energy consumption gap between China and more industrialized countries can be attributed to the large increase in urban household income in China, especially over the past decade with an annual growth rate of 6.5% (China NBS, 2008). As income increases, Chinese households naturally pursue higher living standards, including through owning larger homes and more electronic appliances. At the same time, new neighborhoods also have a greater diversity of conveniences, such as elevators, gyms and recreational landscapes. These changes lead to more energy-intensive consumption patterns. Jinan is among the higher income cities in China (top 10% among the 660 cities), and its residential energy consumption pattern may well represent what other Chinese cities will be like in the near future. Under rapid urbanization, we expect that the share of residential energy consumption in China's energy consumption portfolio will keep increasing, with concomitant increases in GHG emissions.

- ***Implication two: the transition from coal to clean energy sources is critical for the GHG mitigation in the residential sector of China***

As mentioned earlier, coal is the overwhelming primary energy source used in the residential sector of Jinan, accounting for more than 90% of the residential end uses. However, coal is much more carbon intensive than the other primary energy sources. The GHG intensity of coal is about 90-100 ton/GJ, compared to 70 ton/GJ of crude oil and 60 ton/GJ of natural gas (IPCC, 2006). From an on-site consumption perspective, the residential use of gas is still low in Chinese households, mainly for cooking and water heating purposes. Using gas as on-site space heating energy source has much potential to explore, not only enabling household control of heating but also reducing GHG emission. From an electricity generation perspective, increasing the share of nuclear power plants will be an option, as well as promoting electricity-heat cogeneration.

- ***Implication three: the concept of compact development as an energy-efficient pathway is not very instructive under China Context***

Although a large amount of research work has emphasized the importance of compact development, this concept may not be as instructive in China as it is in western countries. From the operational energy consumption perspective, compactness contributes to energy saving in that multi-family buildings have higher thermal efficiency than detached or semi-detached single-family houses. The concept makes much sense for most western countries where single-family houses often dominate the residential sector. For China however, the urban residential sector is already "compact", since nearly all urban neighborhoods consist of mid-rise and high-rise buildings. According to our modeling results, households living in the Enclaves and the Grid would not consume more energy than Superblock households, holding all other variables equal. This suggests that changing the neighborhood form from "compact" to "super compact" (meaning higher presence of high-rise buildings) may not make a difference in household in-home energy consumption; in fact, if compactness comes with homogeneity (as tends to be the case with the current superblock typology), then residential energy consumption may increase.

In the meantime, compactness increases common area energy consumption, indicating a trade-off between land use intensity and energy efficiency. For a 28-floor building, the per household share of common area energy consumption can be as high as 15% of household in-home energy consumption, mainly consumed for elevators and water pumps. Taking this concern into consideration, moderate compactness may be the best choice for urban residential development in China.

- ***Implication four: the Enclave is an energy efficient neighborhood forms for Chinese cities***

According to our analysis, the Enclave is more energy efficient than the other three types of neighborhoods. First, the Enclave has moderate compactness with little or no presence of low-rise buildings, thus it is more thermal-efficient than the Traditional. Second, it "discourages" the on-site consumption of coal, which is the least energy-efficient and the most carbon-intensive. Third, high-rise buildings are rare in the Enclave, so less energy is consumed on elevator and water pump than that in the Superblocks and the Grid. Fourth, the Enclave has diverse land uses and provides many going out options during summer nights so that the AC ownership is reduced; possibly the same case for other devices such as TV and lighting. Fifth, the mid-rise building type, the organized building layout and the moderate building-to-building distance in the Enclave facilitate the utilization of solar energy through the installation of roof solar water heaters. Given these concerns, the Enclave should be an energy efficient neighborhood type to encourage under China urban context.

- ***Implication five: housing choice matters***

The household energy source choice is bundled with the housing choice. When making the housing choice, the household cares about location, neighborhood quality and affordability, and the energy source is only one consideration within this "portfolio". Accordingly, the analysis on household energy source choice should never be isolated from the broad context of housing choice.

Another concern is the home size choice. According to the regression analysis, home construction area is an important determinant of energy consumption. Given a certain budget constraint, households face a tradeoff between home size and location convenience. In neighborhoods with good location, the per square meter housing price is higher so that households can only afford a smaller unit, which renders lower energy consumption. The result indicates that promoting compact development in good locations (transit-oriented development, etc.) can not only reduce transportation energy use but also indirectly reduces residential energy use, although confirming this hypothesis requires more empirical evidence.

- ***Implication six: enabling flexible control of energy consumption can produce considerable energy savings***

As discussed under the electricity energy consumption model, using electricity heating only increases 12.4% of household electricity energy consumption compared to that of households using centralized heating. Based upon the model, an average Superblock household can reduce about 40% total energy consumption if it uses electricity heating instead of centralized heating. The reason is that electricity heating is controllable with regard to temperature setting, usage time and heated area. On comparison, centralized heating is not controllable so it causes excessive consumption. The result suggests that the controllable heating method should be promoted, either by metering centralized heating or promoting electricity heating.

- ***Implication seven: convenience level matters***

High residential energy consumption is not necessarily a bad thing, as long as it increases the convenience level of residents. For instance, the Superblocks consume more energy than the other neighborhood types, mainly because people living there have higher income, live in larger homes and own more appliances. Centralized heating might be more energy consuming than other space heating approaches, but it indeed provides higher convenience. Community facilities and neighborhood landscapes bring about extra increases in common area consumption, but they also make the neighborhood a better place for living. In general, the increase of energy consumption as a result of living quality increase is an irreversible trend in urban China. When comparing different energy consumption patterns, the convenience level should be controlled.

➢ *Implication Eight: the urban design Implication*

As mentioned earlier, this research is part of the "Making Clean Energy City" project supported by the Energy Foundation, and one of the tasks is to develop the "energy pro forma" to help developers and designers to compare the energy performance of different residential development patterns. This thesis research contributes to the project in the following two ways: first, it suggests that the Enclave typology contains several energy-efficient characteristics worth attention of developers and designers in neighborhood design; second, the regression models and the linear estimation framework developed in the research can be used to estimate the base case of neighborhood operational energy consumption, upon which more scenarios can be developed by changing neighborhood design elements. The next step towards the pro forma is to associate the fine-grain design elements, such as density, building orientation and layout, with the thermal, solar and wind impacts, which can be further translated into energy consumption or saving.

8.3 Research Limitations

The research presented in this thesis faces a number of limitations, including:

1) The household electricity, coal and gas consumption data is self-reported rather than metered directly or collected from energy bills, thus we face data accuracy concerns. The issue is especially problematic for gas consumption, since households are highly unsure about how much gas they actually consume.

2) Centralized heating consumption is not metered in China; rather, the heating fee is charged based on the home's constructed area. As such, we estimated centralized heating energy consumption using a city-wide heat load index for residential buildings, but obviously, the heat load index varies significantly across buildings. Since the actual centralized heating consumption per building and home is unknown, we are unable to identify actual variations and their causes.

3) The survey does not account for seasonal variation, so the heating and cooling consumption pattern cannot be examined more in-depth. Moreover, since the survey was conducted in the summer, there might be upward bias in the energy consumption estimates because summer is the peak season for electricity consumption.

4) Data about household behaviors, preferences and attitudes are lacking, such as: home temperature setting, usage pattern of appliances, preferred space heating and cooling approach, length of daily in-home time, neighborhood preferences, lifestyle preferences, satisfaction level, energy use experience, etc. We know such variables influence household energy use, but omitting them in our analysis almost certainly biases our results, in unknown ways. Related to this, we were unable to develop adequate 2-stage models of the simultaneous discrete-continuous choices that better represent the utility-maximizing behavior presumably underlying the household energy consumption processes

5) Some basic household information that helps to explain housing and energy choice is not surveyed, such as the length of residence in current home, how home ownership is obtained, when the heating device is installed, etc.

6) The data about appliance ownership are crude or incomplete, omitting

characteristics such as the appliance type and power and important appliances, such as the clothes washer.

7) The data about home and building physical attributes – which have significant impacts on household energy consumption with regard to space heating and cooling – are especially lacking. Relevant variables include home insulation, home orientation, ventilation, building envelop, inter-building distance, building surface-volume ratio, etc. Without these variables, the fine-grained neighborhood physical form impact on energy use cannot be examined empirically.

8) We were unable to get data about common area energy consumption from property management companies, and we had limited information about relevant physical devices installed, such as elevators, water pumps and lamps in the nine neighborhoods. The estimation of common area energy consumption involves many assumptions applied identically to all neighborhoods, thus some detailed differences across neighborhoods might not be captured.

9) Given time and data constraints, the sample selection bias in the coal consumption models is not yet corrected using the Heckman method.

10) Finally, the modeling approach employed in this thesis is a crude representation of the actual choice process facing households. That is, households may jointly choose among housing, appliance type, fuel type, etc. to achieve a desired standard of living. Such a choice process can be only examined more in-depth with more sophisticated and complex modeling approaches, which may also require additional data.

8.4 Directions for Future Research

As outlined above, perhaps the most critical limitation of the study is data availability. While the current sample size does not seem to be an issue, we lack enough data to reveal fine-grained patterns and influencing factors. Consequently, an immediate extension of the research would be to conduct improved household surveys, covering more detailed topics about preference, behavior, attitudes and appliance usage. In addition, instead of relying purely on questionnaires to collect information, the survey could include quick on-site examination to get extra information about home physical attributes such as orientation, insulation and ventilation.

Furthermore, to improve data accuracy, the household electricity and gas bills (or meter readings) should be obtained directly, rather than relying on household self-reported data. Such data should specifically account for seasonal variations. Meanwhile, it is expected that "smart devices", "smart metering" and other types of information technology-enabled devices and capabilities will soon become fairly mainstream, offering a chance both to improve data collection and improve actual performance by providing immediate feedback to users. With governmental assistance, we would also expect that the neighborhood property management companies would cooperate to provide data about common area device setting and energy consumption.

There are limited solutions to address the data problem for centralized heating. One alternative solution is on-site metering, but this approach would be time and labor intensive and thus difficult to conduct on a large scale. Currently some Chinese cities have been testing the feasibility of meter-based centralized heating fee collection by installing household heat meters. If this approach becomes more widely applied, the data problem will be alleviated.

The causes of the higher likelihood of AC ownership in the Superblocks are worth further examination. In the above analysis we discuss how neighborhood street life may affect household in-home activity and may be underlying the superblock residents' propensity for more AC. However, it is also possible that the Superblocks are just too hot or have bad ventilation so that people have to consume more ACs. To test this hypothesis, it is necessary to conduct thermal and ventilation simulation for a few cases in different types of neighborhoods and make cross comparisons among them.

Future research could also focus on better understanding the urban design/form-sun/wind-energy consumption relationships. The height, shape, orientation and layout of buildings, affect solar gain and wind circulation, thus affecting in-home energy consumption. These factors are normally examined using building-scale simulation tools, and there are fewer demonstrated approaches to understanding how the building approaches "scale" to the clusters and neighborhoods. Hypothetically, these physical attributes and related sun/wind potentials are at least partly conditional on the neighborhood design and form. Furthermore, such effects may vary within the neighborhood, but at a level still beyond the building (i.e., the "cluster"). Quantifying these impacts is important for understanding to what extent neighborhood physical attributes can influence energy consumption, and thus inform more energy efficient design.

The inter-dependency between household housing choice and energy source choice is a very interesting topic worth further exploration. For example, we would imagine that, similar conceptually to the joint discrete-continuous choice process which implies that households' appliance choice is intertwined with desired usage levels, households may choose neighborhoods or housing types based on particular desires for energy sources and consumption levels. For instance a household in favor of using coal as its in-home energy source would choose to live in neighborhoods and building types that facilitate coal use. Using more sophisticated models to analyze such consumption "portfolios" (joint-decisions) may more accurately represent the choice processes. It is also important to examine the "inheritance" of housing and energy source choice. Since in the Chinese context the welfare housing allocation still exists in the governmental sectors and state-owned enterprises, the choice process might actually be restricted from the very beginning. Besides survey questionnaires, some qualitative methods such as face-to-face, semi-structured, interviews would be helpful to reveal the psychological rationale behind the decision making process.

The estimation framework of common area energy consumption can be further improved. When actual energy consumption data become available from property management companies, the equations and parameters of the current framework can be adjusted according to the real world situation. After the adjustment, the framework can be applied to a broader range of neighborhoods in the urban context of China.

The relationship between in-home and out-of-home energy consumption needs to be examined more carefully. In some cases, lower in-home energy use in a certain place may only mean increased energy use elsewhere, such as eating outside instead of cooking in. The net effects on energy use and emissions are important, suggesting a much more complicated analytical structure and broader analytical boundaries.

Finally, operational energy consumption should be combined with transportation and embodied energy consumption to form a full picture of neighborhood lifecycle analysis. Such work has apparently never been conducted in the Chinese context before, and the result will shed light on the orientation of future research, and help identify future energy policy priorities in the residential sector.

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Appendix

Jinan Urban Residents' Residential and Passenger Transport Energy Consumption Survey in 2009

Date:____________ Time:____________ *Questionnaire #____________*

Neighborhood:____________________ Surveyor:_________________ Recorder:_________________

Building Year: ☐Before Liberation ☐1950s ☐1960s ☐1970s ☐1980s ☐1990s ☐2000 or later

Building Construction Structure (# of Stories___) :

☐Timber ☐Masonry Timber ☐Masonry Concrete ☐Reinforced Concrete ☐Steel

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Family and Travel Information

1. There are ______family members in your household, among which ______ of them are employed.

2. Household Type:

☐Single ☐Couple ☐Couple with Kid ☐Parents with Married Children ☐Grandparents and Kid ☐Three Generations

3. Family Members and Weekly Travel Activities:

Family Member	Sex	Age	Occupation	Monthly Income	Weekly Travel Activities					
						Purpose	Mode	Frequency	Distance	Time Taken (min)
1					*weekdays*					
					weekends					
2					*weekdays*					
					weekends					
3					*weekdays*					
					weekends					
4					*weekdays*					
					weekends					
5					*weekdays*					
					weekends					

Sex: a.Male b.Female

Age: a.<20 b.20~30 c.30~40 d.40~50 e.50~60 f.>60

Occupation: a.Teacher/Professor b.Student c.Worker d.Government official e.Company employee f.service/self-employed g.Peasant h.Unemployed i.Retired j. other

Monthly Income: a.below 600 b.600~1,000 c.1,000~2,000 d.2,000~~5,000 e.5,000~10,000 f.>10,000

Trip Purpose：a.work b.school c.shopping d.hospital e.visit,entertainment f.other

Mode：a.walk b.bicycle c.electric bike/scooter d.motorcycle e.taxi f.private car g.company car h.bus/BRT i.company shuttle

Frequency number of trips made per week, a one-way trip counts as one, and a round trip is counted as two trips

Vehicle Ownership and Usage (Select one or two answers)

4. Number of Private Cars__________ *(If zero, jump to the next question）*

Main Purpose of Owning a Car：

☐commute ☐pick up kids ☐shopping ☐leisure and travel ☐household urgencies ☐other _____

(The following question a) b) and c) are for each vehicle)

a) This vehicle is________ years old，annual mileage driven_______，fuel economy_______liter/100km

b) gas_______ yuan/month ；insurance and maintenance_______ yuan/year; other fees _______ yuan/year

c) Parking space（☐own|☐rent）：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐not specified space（street, sidewalk）

5. If your family does not have a car, do you plan to buy one?

☐Yes, main purpose is：

☐commute ☐pick up kids ☐shopping ☐leisure and travel ☐household urgencies ☐other _____

☐No, because：

☐no need of one ☐the vehicle is too expensive ☐gas and maintenance is too expensive ☐congestion

☐lack of parking ☐not environmentally friendly ☐other _____

6. Number of Motorcycles__________ *(The following question a) b) and c) are for each vehicle)*

a) This vehicle is________ years old，annual mileage driven_______，fuel economy_______liter/100km

b) gas_______ yuan/month ；insurance and maintenance_______ yuan/year; other fees _______ yuan/year

c) Parking space（☐own|☐rent）：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐at home/in the yard

☐not specified space（street, sidewalk）

7. Number of Electric Bicycle/Scooter__________*(The following question a) b) and c) are for each vehicle)*

a) This vehicle is________ years old，has changed battery for_______times，needs to charge every______days,; and the power of the vehicle is______KW

b) Maintenance Cost__________yuan/year.

c) Parking space（☐own|☐rent）：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐at home/in the yard

☐not specified space（street, sidewalk）

8. Number of Bicycles________, have lost ______ bicycles ; parking at：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐at home/in the yard

☐not specified space（street, sidewalk）

Residential and Household Energy Consumption

9. You are currently：☐Renting ☐Homeowner ☐Homeowner (still paying mortgage)

10. If renting，the rent is: ____ yuan/month，if still paying mortgage，mortgage payment is: ____yuan/month.

11. Your home has: a) ____bedrooms ， and b) ____dining rooms; c) at the ______th floor （☐top floor）

12. Housing Area：a) Living Area___________M^2，b) construction area ___________M^2

13. Your monthly electricity bill is：___________yuan （or___________Kw.h）

14. Gas Source：☐Natural Gas（pipeline） ☐Coal Gas（pipeline） ☐LPG（gas pitcher_____kg）

Monthly Consumption__________M^3/pitchers （or___________yuan）

15. How much coal does your household consumes each year?___________yuan (identify what kind of coal briquette)

16. Heating facility your household is using：

☐Neighborhood centralized heating，heating bill：__________yuan/season

☐Honeycomb-shaped briquet，average usage amount：__________ton/season

☐Electric heating facility（air conditioning, electric heater） ☐Other(specify)：_________________

17. Main Electric Devices：

☐Air conditioner Count:_____ Power:_____p ☐Refrigerator Count:_____ Size:_____Liter

☐Television Count:_____ Size:_____Liter ☐Desktop Computer Count:_____ Use Frequency:_: hours/day____

18. Type of Water Heater：☐Electric Water Heater ☐Gas Water Heater ☐Solar Power Water Heater

19. Telecommunication: a) internet access at home? ☐Yes ☐No; b) # of cell phones __________ currently in use.

Attitudes towards Travel and Residence

For each statement, express your level of agreement: 1 = strongly disagree, 3 = neutral, 5 = strongly agree

20. Driving is a sign of prestige	1	2	3	4	5
21. Having too many cars is the main reason of traffic congestion	1	2	3	4	5
22. Taking public transit is convenient	1	2	3	4	5
23. I enjoy bicycling	1	2	3	4	5
24. Time spent traveling is wasted time for me	1	2	3	4	5
25. Transportation convenience is important in choosing the residence	1	2	3	4	5
26. I prefer living around people who are similar to me	1	2	3	4	5
27. Living in a gated community is a sign of prestige	1	2	3	4	5
28. I think gated community provides better security	1	2	3	4	5
29. I prefer to have shops and services such as laundry, barber and restaurants	1	2	3	4	5
30. My family pays close attention to saving water, gas or electricity	1	2	3	4	5