ANALYSIS OF ENERGY-SAVING POTENTIAL IN RESIDENTIAL BUILDINGS IN XIAMEN CITY AND ITS POLICY IMPLICATIONS FOR SOUTHERN CHINA

by

Fei Guo

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Energy and Environmental Policy

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LIST OF ACRONYMS

AC	Air Conditioner
ACEEE	American Council for an Energy-Efficient Economy
ADB	Asian Development Bank
AQSIAQ	General Administration of Quality Supervision, Inspection and Quarantine of China
BAU	Business-As-Usual
CAA	Certification and Accreditation Administration of China
CCFL TV	Cold Cathode Fluorescent Lamp Television
CHP	Combined Heat and Power
EEG	Energy Efficiency Gap
EEL	Energy Efficiency Level
EER	Energy Efficiency Ratio
EES&L	Energy Efficiency Standard and Labelling
EIA	Energy Information Administration of the U.S.
EPA	Environmental Protection Agency of the U.S.
EPC	Energy Performance Certificate
FESL	Frozen Energy-Service-Level
FSAC	Fixed-Speed Air Conditioner
GSHP	Ground Source Heat Pump
HSCW	Hot Summer and Cold Winter Climate Zone of China
HSWW	Hot Summer and Warm Winter Climate Zone of China
IEA	International Energy Agency
IESL	Increasing Energy-Service-Level
LCD TV	Liquid Crystal Display Television
LCOCE	Levelized Cost of Conserved Energy
LEED	Leadership in Energy and Environmental Design
LED TV	Light-Emitting Diodes Television

MAP	Maximum Achievable Potential of Energy Savings
MOF	Ministry of Finance of China
MOHURD	Ministry of Housing and Urban-Rural Development of China
NBSC	National Bureau of Statistics of China
NEMS-RDM	National Energy Modelling System - Residential Demand Module
NDRC	National Development and Reform Commission of China
NREL	National Renewable Energy Laboratory of the U.S.
OECD	Organization for Economic Co-operation and Development
PAP	Possible Achievable Potential of Energy Savings
PDP TV	Plasma Display Panel Television
REC	Residential Energy Consumption
SAC	Standardization Administration of China
SEER	Seasonal Energy Efficiency Ratio
THUBERC	Tsinghua University Building Energy Research Center
TRA	Theory of Reasoned Action
UEC	Unit Energy Consumption
VSAC	Variable-Speed Air Conditioner

ABSTRACT

The buildings sector is the largest energy-consuming sector in the world. Residential buildings consume about three-quarters of the final energy in the buildings sector. Promoting residential energy savings is in consequence critical for addressing many energy-use-related environmental challenges, such as climate change and air pollution. Given China's robust economic growth and fast urbanization, it is now a critical time to develop policy interventions on residential energy use in the nation.

With this as a background, this dissertation explores effective policy intervention opportunities in southern China through analyzing the residential energy-saving potential, using the city of Xiamen as a case study. Four types of residential energy-saving potential are analyzed: technical potential, economic potential, maximum achievable potential (MAP), and possible achievable potential (PAP). Of these, the first two types are characterized as static theoretical evaluation, while the last two represent dynamic evaluation within a certain time horizon. The achievable potential analyses are rarely seen in existing literature.

The analytical results reveal that there exists a significant technical potential for residential energy savings of about 20.9-24.9% in the city of Xiamen. Of the technical potential, about two-thirds to four-fifths are cost-effective from the government or society perspective. The cost-effectiveness is evaluated by comparing the "*Levelized Cost of Conserved Energy (LCOCE)*" of available advanced technical measures with the "*Actual Cost*" of conserved energy. The "*Actual Cost*" of energy is

defined by adding the environmental externalities costs and hidden government subsidies over the retail prices of energy.

The achievable potential analyses are particularly based on two key realistic factors: 1) the gradual ramping-up adoption process of advanced technical measures; and 2) individuals' adoption-decision making on them. For implementing the achievable potential analyses in Xiamen, a residential energy consumption (REC) projection model specifically tailored for southern China is developed. This computational model builds on the Kastovich (1982) adoption-decision theory and the general logic and calculation principles utilized in the U.S. EIA's (2003) *Residential Demand Module* of the *National Energy Modeling System (NEMS)*. Base on this projection model, Xiamen's REC from the base year 2011 to 2020 is projected. This model can be used as a policy analysis tool to quantitatively evaluate the real-world impact of diverse policy incentives on residential energy use in southern China.

The projection results show that the MAP of residential energy savings in Xiamen will be about only 8.3-8.4% in 2020 from a business-as-usual projection. Ten current appropriate and feasible policy interventions are evaluated for analyzing the PAP in Xiamen, which reveals that only about one-fourth to one-half of Xiamen's MAP will possibly be achieved in 2020.

Based on the potential analysis for the Xiamen case, a discussion on promoting energy-saving incentive policies for the residential buildings in southern China is given. It suggests that more new, innovative and market-based policies need to be introduced in China in order to realize larger achievable potential for residential energy savings.

Chapter 1

INTRODUCTION

1.1 Motivation

The initial motivation for this research can be traced to two observations. The first comes from the urgency to promote residential energy savings in China, and the second is from the presence of the country's centralized government system, which to a large extent ensures the strong influence of government policies on residential energy savings.

1.1.1 Promoting Residential Energy Savings in China

1.1.1.1 Residential Energy Consumption

Because of China's huge population (1.35 billion in 2012), strong economic growth (9.9% yearly on average from 1980 to 2012 in terms of real GDP- 2005 constant U.S. dollars) and fast urbanization (from 19.4% in 1980 to 47.5% in 2010) during the past decades (World Bank, 2014), residential energy consumption in China is enormous. The residential sector was the second largest energy-consuming sector in China in 2012 (just after the industrial sector), as shown in Figure 1.1. In 2012, the residential buildings in China consumed about 371 Mtoe (million tons of oil equivalent) final energy, which was almost the combined total final energy consumption in both Germany (221 Mtoe) and France (155 Mtoe) in all sectors (i.e., residential, commercial, industrial, transport, etc.) in the same year (IEA, 2014a, 2014b).

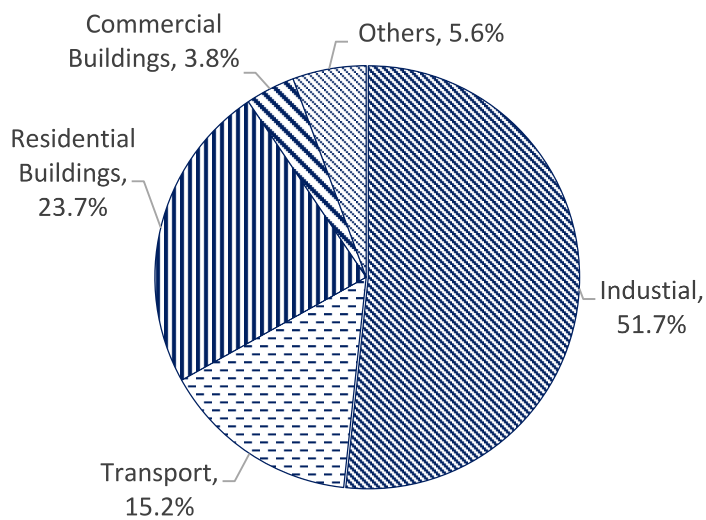
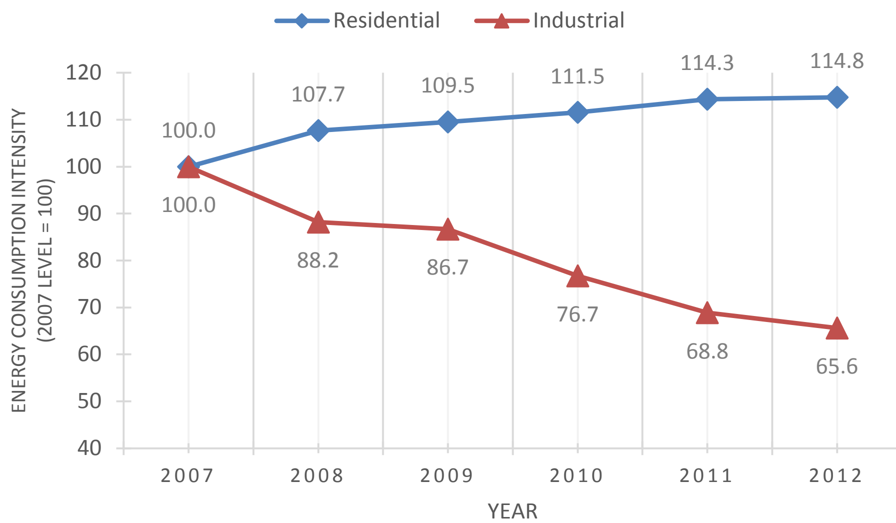


Figure 1.1 2012 Final Energy Consumption Breakdown by Sectors in China

(Source: IEA, 2014a)

1.1.1.2 Residential Energy Intensity

Owing mainly to strong economic growth and the fast improvement of people's quality of life, the residential energy consumption intensity in China has been increasing, as shown in Figure 1.2. Compared with the year 2007, China's residential energy consumption intensity (per capita) was about 14.8% higher in 2012, while the energy consumption intensity in China's industrial sector (per 1000 Chinese Yuan industrial GDP) decreased by about 34.4% during the same period (IEA, 2009-2013, 2014a; NBSC, 2008-2012, 2013).



Note: a) Residential: measured in kgce/capita; Industrial: measured in kgce/1000 Yuan Industrial GDP; b) kgce: kilogram coal equivalent; c) Yuan is the Chinese currency.

Figure 1.2 Energy Consumption Intensity in China

(Sources: IEA, 2009-2013, 2014a; NBSC, 2008-2012, 2013)

1.1.1.3 Energy Performance

The overall energy performance of China's existing residential buildings is far from satisfactory. This is caused principally by two things: the poor quality of the building envelope[1], and the space heating systems in the cold region of China (commonly called northern China).

The energy performance of the building envelope for most residential buildings in China is poor. For instance, the overall heat transfer coefficients of the

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[1] The building envelope is the interface between the interior of the building and the outdoor environment, including the walls, roofs, and windows, etc.

building envelope (measured in watts per meter squared Kelvin) of Beijing's residential buildings are about 1.5-2 times higher than those in Germany which has a climate similar to that of Beijing, shown in Table 1.1.

Table 1.1 Heat Transfer Coefficients of Residential Building Envelopes in Beijing and Germany

Envelope Components	**Exterior Walls** (W/m^2 K)	**Windows** (W/m^2 K)	**Roofs** (W/m^2 K)
Beijing (2012 code)	≤ 0.4	≤ 0.45	≤ 2.0
Germany (2009 code)	≤ 0.2	≤ 0.25	≤ 1.3

(Sources: BCG, 2012; Peng, 2011)

Being the Chinese capital, Beijing has almost the highest insulation requirements for a residential building envelope. This can be easily observed from the difference in requirements between Beijing's building energy code and the Chinese national code (BCG, 2012; MOHURD, 2010a). Therefore, the energy performance of Beijing's residential buildings is usually higher than that of their counterparts in most urban regions in the country. The contrast is even stronger when considering the huge stock of residential buildings in Chinese rural areas, where the building energy performance is poorer than that of their urban counterparts (THUBERC, 2009). Considering these facts, the gap in building envelope's energy performance between China as a whole and advanced countries (such as Germany) might be much more significant than Table 1.1 shows.

In addition to the poor energy performance of the building envelope, most of the existing space heating systems in northern China are plagued with low energy efficiency. With coal accounting for over 75% of China's energy supply (NBSC, 2013), most space heating in northern China adopts coal-fired centralized heating schemes (by coal-fired boilers plants or Combined Heat and Power plants), which inevitably have a lower overall energy efficiency. Low energy efficiency of centralized space heating is mainly caused by the lower energy efficiency of coal-fired boilers (particularly compared to gas-fired boilers), as well as the heat loss during the processes of heat exchange (at heat exchange stations of centralized heating systems) and long-distance delivery lines (by steam or hot water pipelines), aggravated by poor management, operation and maintenance practices. Survey results indicated that the overall energy efficiency of most coal-fired centralized space heating systems (defined as the quotient of energy demanded in buildings divided by consumed coal) in northern China is only about 50-60%, depending on system size and the owner's operation and maintenance practices (Guo, 2003). In comparison, the overall energy efficiency of gas-fired household space heating systems (popular in the U.S. and the U.K.) is usually over 90%.

1.1.1.4 Critical Period for Policy Intervention

In recent years, the floor space of China's building stock has increased very fast owing to a huge investment in property development, which has added about 2.7 billion square meters (over 80% of them in residential buildings) on average annually from 2007 to 2012 (NBSC, 2008-2012, 2013; THURERC, 2013). As a reference, being the third largest economy in the world and having a population of about 126 million, Japan's total building stock is only about 8 billion square meters (Yashiro, 2009). This means that China is constructing the equivalent of Japan's building floor space about every three years. Buildings usually have a rather long life, lasting 40 years or more. Once buildings are constructed with poor energy performance, it is very difficult to retrofit them at a later stage, and quite possible that they will keep standing where they are built, consuming energy inefficiently for decades. Therefore, given China's current fast increase in building stock, the present time offers a crucial period for policy interventions.

1.1.2 The Role of Centralized Government in China

Another observation necessitating this research arises from the presence of strong influence of the central Chinese government on most complex economic-social activities in the nation (CRS, 2013).

Promoting energy efficiency (or conservation) in residential buildings through government policymaking efforts is particularly important because of the large number of stakeholders involved (e.g., governments, investors/banking systems, developers, contractors, owners, tenants, property management companies, and utility companies), and their often conflicting interests on energy efficiency promotion in buildings. In short, the Chinese central government is in a unique position to lead the mission to promote energy savings in residential buildings by designing and implementing effective incentive policies.

The results of a recently conducted survey in China proved the above thesis (IGES, 2013a). In the survey, over 30 Chinese experts (coming from government agencies, universities, and industry) were asked to evaluate the importance of five selected kinds of stakeholders (namely government, developers, building designers, researchers, and residents) on promoting energy savings in buildings by adopting a 5-point scale (the Likert scale). The survey results are shown in Table 1.2. It can be seen that the government is widely viewed as the most influential stakeholder in China, almost approaching the full five points.

Table 1.2 Influence of Stakeholders on Promoting Energy Savings in Chinese Buildings

Stakeholders	**Governments**[1]	**Investors/ Developers**	**Building Designers**	**Researchers**	**Residents**
Influence Factor[2]	4.9	3.7	3.0	2.9	2.7

Note: [1] The central government and local governments are not distinguished in the survey; [2] The Likert-scale of influence factor is: 5- strongest influence; 4-stronger influence; 3-medium influence; 2-weaker influence; 1- weakest influence.

(Source: IGES, 2013a)

This dissertation research focuses on addressing the challenge of deriving residential energy savings from promoting government policies. This initial idea is further developed to specific research questions along with the research process of this dissertation, which will be introduced in Section 1.3 of this chapter.

1.2 Background

1.2.1 Saving Energy to Address Global Environmental Challenges

1.2.1.1 Sustainable Development

With the focus on economic growth, the current dominant socioeconomic development paradigm is often called "modernization," which is usually understood as an interwoven process of industrialization, urbanization and commercialization.

> *Modernization is a special kind of hope. Embodied within it are all the past revolutions of history and all the supreme human desires (Apter, 1987:54).*

> *Modernization lays emphasis on the ever increasing use of science and technical through complex organizations (Dube, 1988:27).*

However, the development paradigm of "modernization" also makes human beings suffer from a broad range of its adverse effects. Environmental degradation is definitely one of them. The environmental challenges that human beings now encounter are quite pervasive (not only locally but also regionally and globally), such as global warming, depletion of natural resources, pollution of air, water and soil, depletion of the ozone layer, acid deposition and extinction of wildlife, etc.

> *No one can deny that past methods of development which focused almost exclusively on short-term economic goals created environmental degradation and social inequities that exist to this day (Scattone et al, 2014:1).*

To deal with the adverse effects of "modernization," particularly triggered by environmental degradation, the interactive relationship between "science, technology and society" (commonly called STS) is carefully reassessed by pioneering scholars. New development paradigms are continuously proposed and discussed, such as post-modernization (Inglehart, 1997), post-development (Latouche,1993), degrowth (Assadourian, 2012), to mention only a few.

A milestone of the proposed new development paradigms is the concept of sustainable development. The term "sustainable" was first used in the Club of Rome's report *Limits to Growth* in 1972, and became a global concern at the 1992 Rio Earth Summit (UN Conference on Environment and Development). At that time, people started to learn and to accept, intentionally and unintentionally, the long ignored concept that our economic growth or development should not go beyond the carrying capability (or called ecological limits) of our home planet, the Earth.

The most widely recognized definition of sustainable development is seen in the United Nations report *Our Common Future* in 1987 (often called the Brundtland Report), in which sustainable development is expressed as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987:43)." By emphasizing both intra-generational and inter-generational equity, sustainable development is often viewed as a holistic and equitable framework of development by integrating social, economic and environmental goals and objectives.

> *Shifting to SCP (sustainable consumption and production) involves complex systemic issues. For SCP to be practically implementable as a goal would require nothing short of a critical review of the culture of consumerism that has become pervasive through mass media and advertisements, has been internalized by billions of consumers around the world and which has come to define modern*

macroeconomic thinking and the existing economic system (Akenji and Bengtsson, 2014: 519).

Energy use closely relates to economic growth and people's quality of life, especially in developing countries (Pasten and Santamarina, 2012). Energy services contribute to industrial growth, enhanced productivity and the involvement to global markets and trade. Given the fact that the developed nations surpass the less developed nations on many human development indicators (such as ample food and clean water, lower infant mortality, etc.), it has long been found that per capita energy consumption are highly correlated with economic development and modern lifestyle. Energy is also central to many air pollution issues. Use of fossil fuel is responsible for particle pollution, sulfur oxides emissions, nitrogen oxides emissions, which contribute to smog, acid rain, and haze (EPA, 2015).

> *There are profound environmental impacts arising from the energy system-from obtaining energy feedstock, generating energy, using energy, and also from all the supporting activities and infrastructure (Howard et al., 2011: 295).*

As energy has a deep and broad relationship with each of the three core pillars of sustainable development (i.e., economy, environment, and social welfare) (OECD, 2001), reducing the energy consumption (or consumption intensity) of human society is widely viewed as a crucial component for sustainable development.

1.2.1.2 Climate Change

Along with the process of modernization, the scale on which humankind can impact the global climate system has increased dramatically. The process of modernization contributed to a dramatic rise in the global population, from about 1 billion in the beginning of Industrial Revolution to current about 7 billion (UNDESA, 2012), which spurred more demand for energy, increased need in agricultural land and accelerated deforestation, and led to the climate change problem (Downie et al., 2009). According to the IPCC (2013: 5, 17), “the total temperature increase between the average of the 1850–1900 period and the 2003–2012 period is about 0.78 ℃,” and “it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas (GHG) concentrations and other anthropogenic forcings together.”

Mitigating anthropogenic climate change has been on the global agenda since the 1990s, and the UNFCCC and the Kyoto Protocol stand at the center of international climate policy. To mitigate climate change, substantial and sustained reductions of GHG emissions are required (IPCC, 2013; Yang 2013). As about 65% of human-induced GHG emissions come from energy consumption due to human activities (IEA, 2012), reducing energy use, therefore, becomes one of the most significant measures for mitigating climate change. The energy saving potential may be significant. According to Yang (2013:10), “a review of the IEA literature on the potential for energy efficiency improvements in the past and the future demonstrates that energy efficiency potentials in selected IEA/OECD countries from 1975 to 2030 would be within a range of 20–50%,” and “the potential for energy efficiency savings in developing countries could be higher than IEA/OECD countries because of the widespread use of inefficient energy technologies.”

1.2.1.3 Section Summary

Achieving energy savings is certainly a crucial strategy for both shifting to the paradigm of sustainable development and globally mitigating climate change - two highly-focused international challenges on the global agenda at present, shown in Figure 1.3.

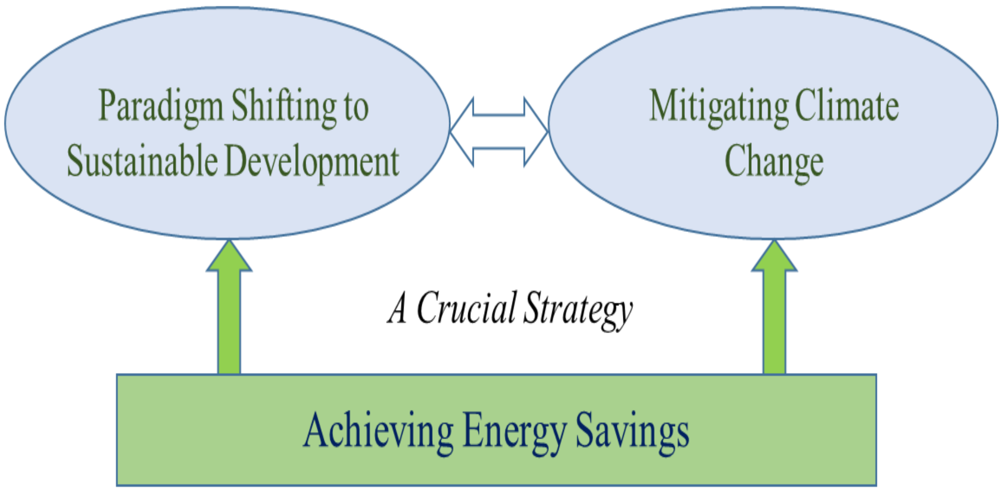

Figure 1.3 Energy Savings as a Crucial Strategy to Addressing Urgent Global Challenges

(Sources: Based on OECD, 2001; IPCC, 2013)

1.2.2 Residential Buildings to Achieve Energy Savings

Buildings accounted for about **34.2%** of the total final energy consumption in the world in 2012, bigger than the industrial and transport sectors (IEA, 2014a). Table 1.3 presents the final energy consumption breakdown by sectors in some selected countries. It can be seen that in many countries, such as Japan, Germany, France, the

U.K., India, and many ASEAN member countries[2], the buildings sector is the largest energy consuming sector.

Table 1.3 Final Energy Consumption Breakdown by Sectors in 2012

Sectors	**Industrial**	**Transport**	**Building**	**Agriculture & Others**
World	31.1%	30.7%	**34.2%**	4.0%
U.S.	18.7%	45.0%	34.0%	2.3%
Japan	30.2%	27.5%	40.8%	1.5%
Germany	28.0%	26.7%	45.1%	0.2%
France	19.5%	31.0%	45.1%	4.4%
U.K.	19.9%	32.2%	46.2%	1.7%
China	51.7%	15.2%	27.5%	5.6%
Thailand	40.0%	29.9%	24.6%	5.5%
India	35.3%	15.4%	42.2%	7.1%
Philippines	26.9%	35.2%	36.9%	1.0%
Indonesia	25.1%	29.7%	43.2%	2.0%
Vietnam	39.8%	22.1%	36.9%	1.2%
Myanmar	12.4%	7.5%	76.2%	3.9%

Note: a) The final energy consumption here excludes the amount of energy that is used as raw materials and is not consumed as a fuel or transformed into another fuel.

(Sources: IEA, 2014a, 2014b)

[2] ASEAN (Association of Southeast Asian Nations) is a political and economic organization of ten countries located in Southeast Asia, including Indonesia, Malaysia, the Philippines, Singapore, Thailand, Brunei, Cambodia, Laos, Myanmar and Vietnam.

At the global scale, approximate three quarters of the energy used by buildings is consumed by residential buildings. For most of the Asian developing countries (e.g., China, India, most ASEAN member countries), this share is even as high as over 85% (IEA, 2014a). Therefore, the residential sector is crucial for achieving significant energy savings, and should be given high priority on the energy policymaking agenda.

1.2.3 Features of Residential Buildings Sector

Although the residential buildings sector is crucial for energy savings, it is often ignored or put at much lower priority by policymakers in many developing countries. Byrne and Wang (2014:11) stated that “our current built environment has become difficult to change given policy and economic priorities that emphasize short-term gains, fast construction, and low-cost finance.” For instance, an assessment (IGES, 2013b) shows that although the building sector is the largest energy consuming sector in the Philippines, the primary priorities of national energy policies were heavily put on the transport and industrial sectors, and the energy-saving incentive policies for buildings in the country were usually the by-products of the energy policies designed for other purposes (mainly through the policy scope extension).

Compared with energy conservation progress in the industrial, transport and commercial buildings sectors, progress in the residential buildings sector seems much more sluggish, particularly in developing countries (OECD, 2003). This fact is, to a large extent, attributed to some unique features of the residential sector itself, such as the long-life of buildings, “principal-agent” problem in leased buildings, involvement of a large number of interests-conflicting stakeholders, and low standardization of building components. These unique features have caused significant barriers for achieving energy savings in residential buildings.

1.2.3.1 Long-Lived Nature of Buildings

Buildings usually have a rather long life (several decades). The long-lived nature of buildings automatically results in a low turnover rate of the building stock and significantly affects the choice of related policy instruments. The turnover rate of residential buildings in the OECD countries is usually only about 1-1.5%, much lower than for automobiles at 10% (OECD, 2003). The low turnover rate means that it is difficult for advanced (or high efficiency) technical measures to be incorporated into the existing building stock, while the obsolete technologies will have a long life span.

1.2.3.2 Principal-Agent Problem in Leased Buildings

A significant percentage of residential buildings is not occupied or used by their owners, but leased to tenants. For example, in many selected OECD countries over 30% of the housing stock is occupied by tenants (OECD, 2003); in China, the share is about 32% in the city of Beijing and 29% in the city of Xiamen according to a recent survey (IGES, 2013a).

For leased residential buildings, owners usually do not have adequate initiatives to invest in the energy performance improvement of their buildings mainly because the energy cost of living in them goes to tenants and the energy performance of buildings is not reflected in the rent. In other words, the building owners could not directly benefit from the energy efficiency improvements in their buildings. On the other hand, the tenants usually do not have such initiatives either, mainly because the payback time of such investment is often much longer than the tenants' leases. In short, both of the owners and tenants lack adequate initiatives to promote energy efficiency in leased buildings. Such a deadlock is called "principal-agent" problem

(OECD, 2003). Therefore, specific policy instruments may need to be applied for leased buildings, compared to owner-occupied buildings.

1.2.3.3 The Large Number of Stakeholders

The life cycle of buildings can be generally divided into three stages: design, construction and operation. Each stage has its own significant and specific influences on the formation of the energy performance of buildings. Accordingly, a large number of stakeholders are involved in promoting energy savings for residential buildings, including governments, investors and developers, designers (such as architects, structural, mechanical and electrical engineers), owners and tenants, property management companies, and utility companies, etc. The interests of these stakeholder groups are often inconsistent with the mission of promoting energy savings in buildings, which has become a significant barrier for residential energy conservation.

1.2.3.4 Low Standardization of Buildings Components

Compared to other durable products (like vehicles), the level of standardization in buildings is quite low (OECD, 2003). Table 1.4 shows the standardization level of vehicles and housing. Part of the reason for the low standardization level of housing may be because of the dominance of a large number of small construction companies in the buildings sector. The wide adoption of a large number of non-standardized components in housing has caused a serious barrier in controlling and improving the energy performance of these components, and, therefore, that of buildings as a whole.

Table 1.4 Standardization Level of Vehicles and Housing

	Number of kinds of components used in one unit[2] (A)	Total number of alternatives for all components (B)	Average total number of alternatives per kind of components (B/A)
Vehicles[1]	1,800	3,700	2
Housing	1,900	19,000	10

Note: [1] The selected model of vehicles is the model that has the largest sales volume in 1999; [2] Excluding small units for connecting components such as bolts and nuts.

(Source: OECD, 2003)

The features mentioned above make achieving energy savings in residential buildings a difficult goal for policymakers. This may partly explain why the residential buildings sector is often a low priority on the energy policymaking agenda.

1.3 Research Questions

Despite being a key strategy in pursuing sustainable development and mitigating climate change, achieving residential energy savings is a difficult challenge, particularly compared to policymaking in other sectors (e.g., industrial, transport, commercial buildings, etc.) (OECD, 2003). This fact may be largely attributed to the residential buildings sector's previously mentioned features, namely the long-lived nature of buildings, the involvement of many stakeholders, the "principal-agent" problems, and the low standardization of building components.

To successfully achieve residential energy savings, promoting the current incentive policies is a crucial step. This is especially the case in a country like China given the strong influences of government policies on socioeconomic activities. In fact, the scale of energy-saving potential is often one of the primary concerns of policymakers when they begin to consider improving existing incentives or designing new incentive policies.

Accordingly, this research focuses on exploring effective policy intervention opportunities through analyzing residential energy-saving potential in China.

The scope of this research is limited to examining Chinese urban residential buildings for two reasons. First, residential buildings in rural China are not regulated by current governmental policies (e.g., construction permits, mandatory building energy code[3], on-site inspections). This is mainly because they are mostly self-constructed and have only a simple structure (e.g., one or two floors). Second, Chinese rural households consume much less commercial energy (i.e., excluding self-collected biomass) than their urban counterparts, owing primarily to a lower household income and the lack of energy supply infrastructure. In 2012, the average income in Chinese urban households was about three times higher than that of rural households (NBSC, 2013). As a consequence, biomass consumption almost accounted for 70% of the total energy consumption in Chinese rural households in 2008 (Yao et al., 2012), and, accordingly, the commercial energy consumption intensity in Chinese rural households is only about half of that of their urban counterparts (THUBERC, 2013).

China has no comprehensive and authoritative national database, such as the "Residential Energy Consumption Survey" in the U.S. Given China's diverse climates

[3] At the end of 2012, the Chinese governments issued a voluntary building energy code for rural residential buildings, "Design Standard of Energy-efficient Rural Housing (GB/T 50824-2013)".

and lack of established data, this research focuses on the Chinese city level instead of the national level.

In addition, this research targets the cities in southern China because of the involvement of centralized space heating in northern China. In China, a geographic line for the adoption of centralized space heating was drawn by the central government based primarily on climate differences. This line is often called the “Qin Mountains and Hui River Line,” which is generally along the line of north latitude 33°, as shown in Figure 1.4. North of this line, centralized space heating is essential for urban areas; south of this line, no such systems are in operation.

Figure 1.4   The Geographic Line of Centralized Space Heating in China

(Source: Pangbo News, 2014)

As a holdover from China's old Soviet-style planned economy, centralized space heating in northern China contains several specific features. First, it has long been viewed by the general public as an important government-provided social welfare; second, most of the space heating providers are state-owned firms; third, with a government-decided fixed rate (e.g., 3 or 4.8 US$/m^2 per heating season in Beijing[4]), space heating billing is usually based on residents' housing floor space rather than their actual heat consumption; and fourth, governments regulate the duration of the heating season. For example, the nominal heating season in Beijing is from November 15 to March 15 of the coming year; however, if the government of Beijing thinks that it is needed, all of the heating firms in the city could be required to start their heating service earlier or to stop the service later without extra heating charges for residents.

Given the Chinese governments' high concern with centralized space heating's traditional role as an important social welfare service, achieving energy-savings from space heating in China relates not only to simply adopting advanced technical measures, but relates more closely to changing the old ideas held by the governments and the general public, which is complicated, challenging and time-consuming. Therefore, compared to all the other end uses of residential energy consumption[5], achieving energy savings from space heating in China is particularly difficult and

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[4] The heating charge of 19 RMB/m^2 (about 3 US$/m^2) is for coal-fired heating systems, and, for gas-fired heating systems, the charge is 30 RMB/m^2 (about 4.8 US$/m^2) in Beijing (BMCDR, 2013).

[5] Including space cooling, cooking, lighting, water heating and plug-in appliances (both centralized water heating and space cooling are rarely seen in Chinese urban residential buildings).

more complex. As a consequence, space heating is usually singled out as a separate area for studying the energy consumption in China buildings[6] (THUBERC, 2013; Xiao et al, 2014).

Based on the above discussion, a city in southern China will be selected serving as the case study in this research. It needs to be noted that the residential energy consumption excluding space heating in China does not vary much between the northern and southern China (THUBERC, 2013). This means that the research findings from the cities in southern China can be also representative of the final energy consumption excluding heat for space heating in northern Chinese urban residential buildings.

To guide the research, two specific questions are proposed.

Q1: How should residential energy-saving potential be analyzed in southern Chinese cities (using a selected city as case study)?

Q2: What information from the potential analysis could be revealed for effective policy interventions in southern urban China?

[6] The research related to energy consumption in Chinese buildings are usually divided into four fields: space heating in north urban China, residential energy consumption excluding space heating in urban China, rural residential energy consumption, and energy consumption in commercial buildings.

1.4 Selection of the Case Study City

1.4.1 Focusing on Relatively Small Scale Chinese Cities

In general, Chinese cities can be divided into five tiers according to their population (State Council, 2014). The tiers are megacities (over 10 million, such as Beijing, Shanghai, Guangzhou, etc.), extra-large scale cities (5-10 million, often called regional hub cities, such as Nanjing, Wuhan, Chengdu, Xi'an, etc.), large scale cities (1-5 million), medium scale cities (0.5-1 million), and small scale cities (less than 0.5 million).

In order to be more representative of China, this research centers on cities with a population less than 5 million for two prime reasons. First, compared to megacities and regional hub cities, these cities usually lack the capacity (e.g., governance, institutions, financing, human resources, etc.) to design and issue their own local energy-saving incentive policies. Consequently, they use mostly national policies. Therefore, they are more appropriate showcases for examining national policies. Second, these cities host the vast majority (approximate 80%) of the Chinese urban population (about 740 million) (NBSC, 2014). Table 1.5 shows the distribution of Chinese cities by population.

Table 1.5 Distribution of Chinese Cities by Population 2013

Population Size		≥ 10 million	5-10 million	≤ 5 million
Northern China	Numbers of Cities[1]	2	4	126
	Ratio of Urban Population[2]	3.1%	3.3%	37.0%
Southern China	Numbers of Cities[1]	3	9	143
	Ratio of Urban Population[2]	5.9%	8.6%	42.1%

Note: [1] Prefectural-level cities and above; [2] Using 2013 Chinese total urban population (about 740 million) as the baseline.

(Source: NBSC, 2014)

1.4.2 Selecting Xiamen as the Case Study City

The city of Xiamen serves as the case study for this dissertation research. It lies in the Fujian province of southern China and has a population of about 3.61 million (XBS, 2012a). Xiamen belongs to the southern part of China's "Hot Summer and Warm Winter (HSWW)" climate zone, with an all-year-round average temperature of about 21 ℃ (XBS, 2012a). Therefore, space heating in Xiamen is almost not needed. The location of Xiamen is shown in Figure 1.5.

Figure 1.5 Location of Xiamen City in China

(Source: Vacations-to-go, 2015)

Being one of the five pilot cities in the beginning stage of China's "reform and opening-up" policy, Xiamen has established a relatively complete city statistical data system, which brings a significant advantage in data collection for this research. In addition, as one of the more economically developed cities in China, the per capita GDP in Xiamen is about two times that of the national average (NBSC, 2013; XBS, 2012a). Therefore, the residential energy consumption (REC) in Xiamen can be indicative of Chinese future REC levels, given the country's robust economic growth, fast urbanization and continuous improvement of people's quality of life. Therefore, exploring the energy-saving potential in Xiamen's residential buildings can not only help to evaluate potential for currently developed urban areas in China, but can also be a valuable guide as a predictive example for the less developed areas in the country.

For the above reasons, Xiamen was selected as the case study city used to examine the methodology proposed in this research.

1.5 Organization of Chapters

There are six chapters in this dissertation. Chapter 1 has provided an introduction to the motivation, background and specific research questions of this research. In Chapter 2, a comprehensive assessment on China's current energy-saving incentive policies for buildings is presented. Chapter 3 goes over the methodology adopted in this dissertation, mainly including related conceptual frameworks, calculation and analysis approaches, and data collection methods, based on broader literature review. Chapter 4 introduces the data collection for the Xiamen case study. In Chapter 5, the residential energy-saving potential in the city of Xiamen is calculated and analyzed. Conclusions and suggestions for future research work will be presented in Chapter 6.

Chapter 2

REVIEW OF ENERGY-SAVING POLICIES FOR BUILDINGS IN CHINA

As stated in Chapter 1, the primary focus of this dissertation is to improve energy-saving incentive policies through the analysis of energy-saving potential. A comprehensive and critical assessment of current energy-saving policies for buildings in China provides the basis of this analysis[7]. Through this assessment, the general strengths and weaknesses of current incentive policies can be observed. This chapter presents a critical review of current energy-saving policies for buildings in China.

This chapter contains four sections. The first section introduces the authority levels, the legal foundation and key organizations for energy-saving policymaking for buildings in China. The second section contains a brief history of China's energy-saving incentive policies for buildings. The third section provides a detailed review and assessment of the main energy-saving policies for buildings in China. The last section summarizes main findings from the policy review.

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[7] Although this dissertation focuses only on residential buildings in China, many energy-saving policies apply to both residential and commercial buildings. Therefore, in this chapter, the term of "energy-saving policies for buildings" is used instead of "energy-saving policies for residential buildings."

2.1 Introduction to China's Energy-Saving Policymaking for Buildings

2.1.1 Policymaking Levels in China

According to the *Legislation Law of China* (enacted in 2000), in addition to the Chinese Constitution, policymaking in China is generally divided into four levels: national laws, administrative regulations, national administrative rules (or local decrees at the same level), and local administrative rules (NPC, 2000). These range from high to low in levels of legal authority, as shown in Figure 2.1.

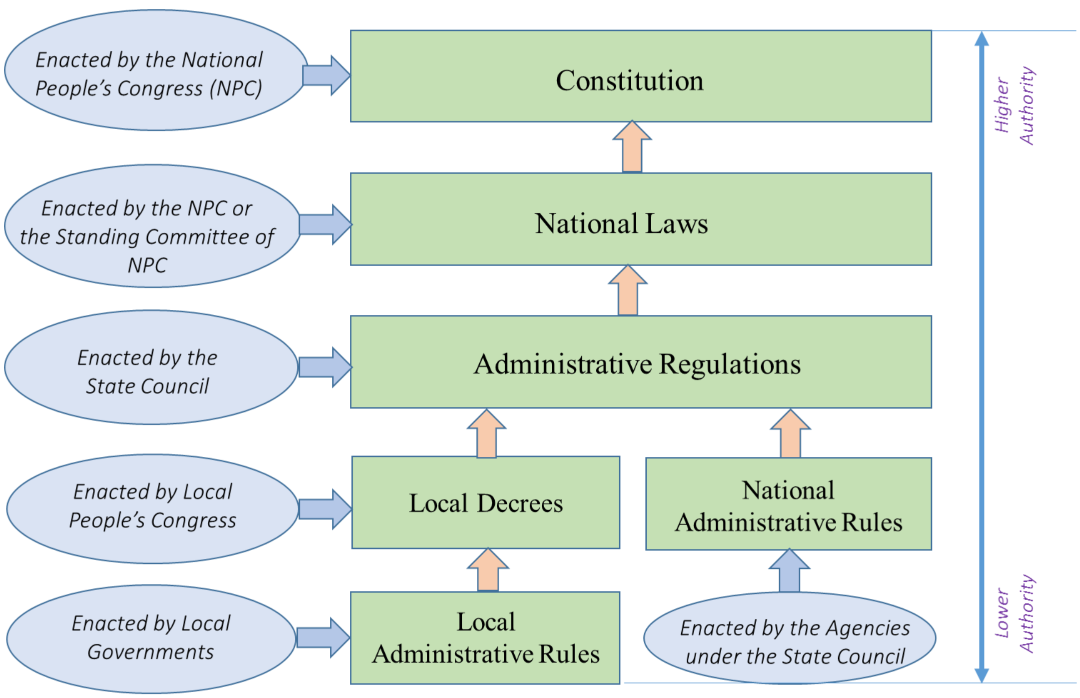

Figure 2.1 Policymaking Levels in China

(Source: NPC, 2000)

As shown in Figure 2.1, each level of policy can be issued only by specific kinds of organizations (NPC, 2000).

- "National Laws" are issued only by the National People's Congress (NPC) or its Standing Committee when the NPC is in recess;
- "Administrative Regulations" are issued only by the State Council (the supreme executive organization in China);
- "Local Decrees" are issued by local People's Congresses (provincial or city level), and "National Administrative Rules" are issued by the agencies under the State Council (e.g., the MOUHRD, NDRC and MOF[8]);
- "Local Administrative Rules" are issued by local governments (i.e., provincial, city, county) and implemented in their jurisdictions;

Although the administrative regulations, local decrees, and administrative rules are not strictly laws in the country, they are often used as very important references for judging lawsuits by the Chinese People's Courts at different levels (NPC, 2000). Being issued by the State Council, administrative regulations are usually viewed as having almost the same legal authority as national laws. This fact is understandable because administrative regulations are often the primary sources of national laws, and many of them finally turn into national laws after a certain time of trial enforcement.

Although China's policymaking framework is rather straightforward, specific mechanisms are designed to solve potential conflicts among policies issued by

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[8] MOUHRD (Ministry of Housing and Urban-Rural Development), NDRC (National Development and Reform Commission) and MOF (Ministry of Finance) are the three core agencies under the State Council for the design and issuance of energy-saving related policies for buildings in China.

different government organizations. Such potential conflicts include those "between local decrees and national administrative rules," "among various national administrative rules," and "between national administrative rules and local administrative rules" in some rare cases. For all these possible conflicts, the State Council is authorized to make a final ruling (NPC, 2000).

In short, there are two significant characteristics related to policymaking in China. The first one is the importance of "administrative regulations and rules." For certain historical reasons, the "national laws" in China are not well developed, although China has expedited its legislative efforts during the past two decades. As a consequence, there are still many blank areas left in the nation that are actually governed by "administrative regulations or rules." Another significant characteristic is the presence of a strong centralized government system (i.e., the State Council). The State Council's work can be seen in the policymaking hierarchy in China as well as in the mechanisms designed to solve possible conflicts among the policies at different authority levels.

2.1.2 Levels of Energy-Saving Policies for Buildings

According to China's policymaking levels (see Figure 2.1), the energy-saving policies for buildings in the nation can be generally divided into three levels. From highest to lowest in authority they are the "national law" level (issued by the NCP or its Standing Committee); the "administrative regulation" level (issued by the State Council); and the national or local "administrative rule" level (issued by the agencies under the State Council or local governments). These levels are shown in Figure 2.2.

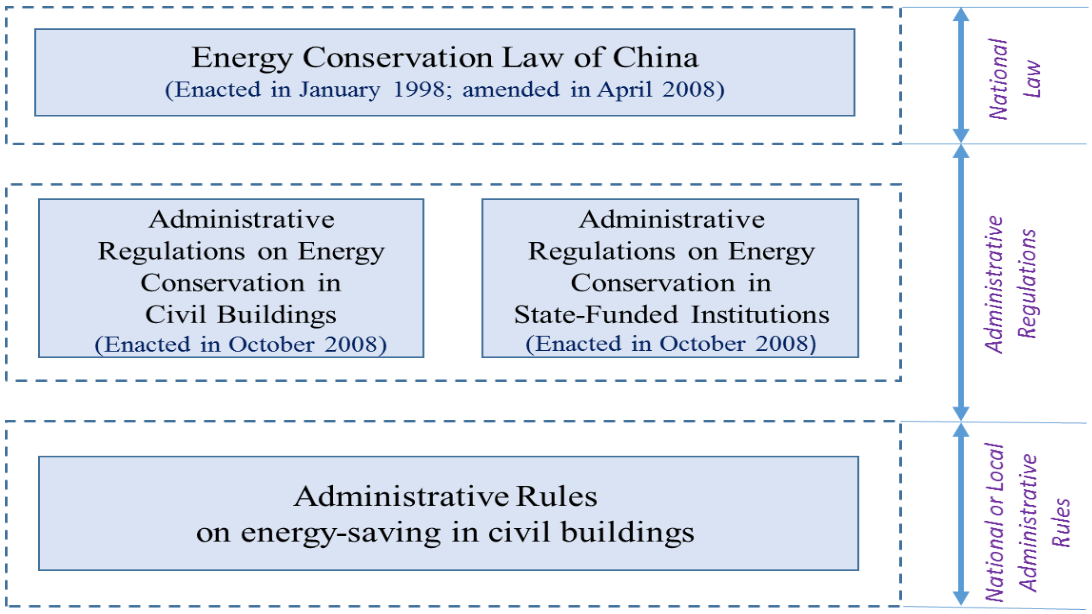

Figure 2.2 Levels of Energy-Saving Policies for Buildings in China

(Sources: Based on NPC, 2008; State Council, 2008a, 2008b)

The *Energy Conservation Law of China* (first enacted in 1998 by the NPC and amended in 2008) is the most important national law for energy savings in China[9] (Tu, 2010). It holds the highest legal authority to implement energy-saving activities in the nation. To assist in the enforcement of this law in the buildings sector, two key administrative regulations were issued by the State Council in 2008. They are *Regulations on Energy Conservation in Civil Buildings*, and *Regulations on Energy Conservation in State-Funded Institutions*. These three legislative documents form the

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[9] The name of the law is translated as "energy conservation"; however it actually targets a broader scope of "energy savings." The word "Jie Neng (节能)" in Chinese means both "energy conservation" and "energy savings."

legal foundation for achieving energy savings in Chinese buildings[10]. To support the enforcement of these three crucial legislative documents, a number of administrative rules at different levels were issued. These will be introduced in detail in Section 2.3.

Moreover, a vertical "executive agency system" for the enforcement of energy-saving policies for buildings has been well-established in China (see Figure 2.3).

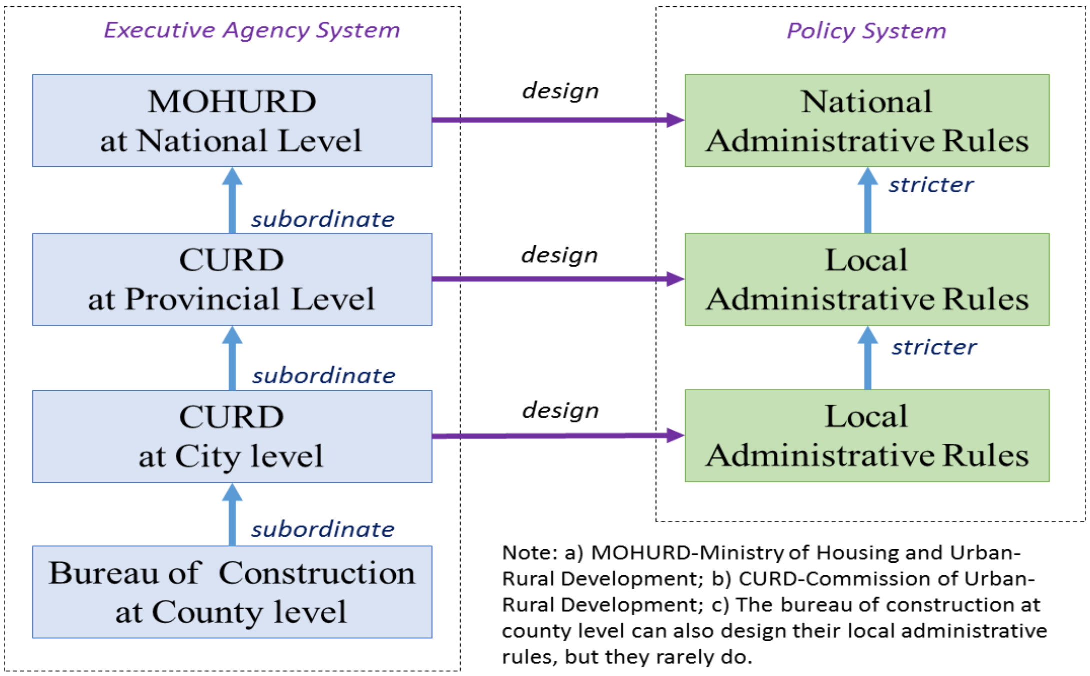

Figure 2.3 Executive Agency Structure for Enforcing Energy-Saving Policies for Buildings in China

(Sources: Based on Tu, 2010; Kang, 2008)

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10 It must be noted that although administrative regulations are, strictly, not laws in China, they have almost the same level of authority as national laws.

At each level of local government, an executive agency (usually called the "Commission of Urban-Rural Development" at the provincial and city level, and "Bureau of Construction" at the county level) is authorized to enforce national and local policies in its jurisdiction[11]. Such a vertical executive agency system and the presence of a strong Chinese national government could serve to enhance the wide enforcement of national energy-saving policies for buildings in the nation.

2.1.3 Legal Foundation of Energy-Saving in Buildings

2.1.3.1 China's Energy Conservation Law

The *Energy Conservation Law of China* states that energy conservation is one of the fundamental national policies of China, and resides among the highest priorities of the country's energy development strategies (NPC, 2008).

The 2008 amended edition of the 1998 law incorporated two significant revisions. First, the third chapter of the law (with a title of "Rational Energy Utilization"), which was very brief and general in its original 1998 edition, was expanded to include six detailed sections, including a section on "Energy Conservation in Buildings." Second, a new chapter entitled "Incentives" was added.

There were seven articles stipulated in the new section of "Energy Conservation in Buildings." The new edition of law clearly states: 1) governments at various levels must take the responsibility to achieve energy savings in buildings; and

[11] Primarily restricted by institutional, financial and human resources, usually only the most economically-developed provinces and megacities in China (e.g., Beijing, Tianjin, Guangdong, etc.) are able to design and issue their local energy-saving policies for buildings.

2) during the sale of buildings, buildings sellers must inform buyers of the adopted energy-saving measures in sales contracts (NPC, 2008). In the new fifth chapter of "Incentives," the law requires that: 1) governments at different levels (both central and local) should arrange a certain amount of appropriation from their budget for energy-saving activities annually; 2) governments should encourage financial institutions to increase their credit to energy-saving projects (NPC, 2008).

2.1.3.2 Key Administrative Regulations

Despite the fact that the *Energy Conservation Law of China* has been extensively amended since its original 1998 edition, the articles in the new edition were still too vague to effectively guide the government's work in a practical way.

In order to facilitate and strengthen the implementation of the law in the buildings sector, the State Council issued two administrative regulations in the same year (2008), namely *Regulations on Energy Conservation in Civil Buildings*, and *Regulations on Energy Conservation in State-Funded Institutions*. These two administrative regulations are in accordance with Section 3.3 (Energy Conservation in Buildings) and 3.5 (Energy Conservation in the State-Funded Public Institutions) of the 2008 edition of the law.

Enacted by the State Council Order No. 530, the *Regulations on Energy Conservation in Civil Buildings* specifically state that: 1) a building will not be issued "permit of planning design on the land" and "permit of construction" if its planning and design are not able to meet current building energy codes; and 2) local governments must make working plans for retrofitting existing buildings with funding support from both the governments' budget and building owners' private investment (State Council, 2008a). Moreover, certain penalties, including fines, license suspension, administrative liabilities and even criminal liabilities, are included in the regulation to ensure achieving energy savings in buildings.

The *Regulations on Energy Conservation in State-Funded Institutions* was issued through the State Council Order No. 531. The primary purpose in issuing this regulation is to make state-funded (fully or partly) institutions (e.g., government buildings, public schools and hospitals, etc.) play a leading role in energy-saving in buildings in the country (State Council, 2008b).

Table 2.1 summarizes the number of articles that are specifically related to the buildings sector in the *Energy Conservation Law of China* and the two follow-up administrative regulations. It can be seen that the related articles have been largely expanded from twelve in the law to a total of eighty-six in the two administrative regulations.

Table 2.1 Number of Building-Related Articles in the Energy Conservation Law of China and the Two Follow-Up Administrative Regulations

Legislative Documents	**Energy Conservation Law of China**		**Administrative Regulations**	
	Section 3.3 (Energy Conservation in Civil Buildings)	Section 3.5 (Energy Conservation in the State-Funded Public Institutions)	Regulations on Energy Conservation in Civil Buildings	Regulations on Energy Conservation in State-Funded Institutions
Number of Articles	7	5	44	42

(Sources: Based on NPC, 2008; State Council, 2008a, 2008b)

2.1.4 The Ministry of Housing and Urban-Rural Development (MOHURD) - Principal Policymaking Agency

Being one of the agencies under the State Council, the MOHURD is the highest policymaking body for energy savings in Chinese buildings[12]. The MOHURD comprises 15 departments with over 300 staff. According to the State Council's document (2008-No.74), one of the MOHURD's thirteen responsibilities is promoting energy conservation in buildings, and reducing carbon emissions of cities and towns through making energy-saving policies for buildings, and supervising their implementation (MOHURD, 2014).

The "Department of Building Energy Conservation and Technology (DBECT)" under the MOHURD is primarily in charge of the related policymaking and enforcement in China (MOHURD, 2014). The DBECT regularly issues national working plans for promoting energy savings in buildings. Such plans are usually called "Energy Conservation Plans in Buildings (ECPB)", and are often issued in coordination with each of China's Five-Year-Plan (FYP)[13]. The current ECPB is designed for implementing the 12th FYP (2011-2015), and focuses primarily on four tasks: 1) compliance with building energy codes; 2) retrofits of centralized space heating systems in northern China; 3) retrofits of existing buildings; and 4) the adoption of building envelope components with high energy performance (MOHURD, 2012a).

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[12] The MOHURD is the successor the previous Ministry of Construction (MOC).

[13] The Five-Year-Plan (in full name called *National Development Five-Year-Plan*) is the chief socioeconomic development plan in China, and has been issued by the State Council since 1953.

2.2 A Brief History of Energy-Saving Policies for Buildings

The earliest Chinese policymaking efforts on energy savings in buildings can be traced back to 1986 when two milestone documents were issued: *Administration Regulations on Energy Conservation Management (Interim)* by the State Council and *Design Standard for Energy Conservation in Civil Buildings (JGJ26-1986)* by the Ministry of Construction (the predecessor of the MOHURD) (CSTC, 2010; Tu, 2010). Since that time, the development of China's energy-saving policies for buildings can be generally divided into three successive phases.

2.2.1 The First Phase (1986-2000)

During this period, policymakers were focused largely on the energy consumption of space heating for residential buildings in northern China. The primary milestone of this phase was the issuance of the first building energy code in China (i.e., JGJ26-1986). This code targeted only the northern Chinese residential buildings, and stipulated detailed requirements on the energy performance of the building envelope as well as attached centralized space heating systems (MOHURD, 1986). Implementation of this code was expected to save about 30% in energy consumption (measured in energy use for space heating) in new buildings compared to baseline buildings (i.e., existing stock of northern Chinese residential buildings in 1981-1982). In 1995, the code was revised to pursue 50% of energy savings from the "1981-1982 baseline" level (Kang, 2008). In short, the scope of China's energy-saving policies for buildings was quite narrow before 2000. China focused exclusively on the space heating energy consumption in its northern residential buildings.

2.2.2 The Second Phase (2001-2005)

After 2001, the scope of Chinese energy-saving policies for buildings was largely expanded to cover residential buildings in southern China, commercial buildings, as well as some important household appliances (i.e., refrigerators and air conditioners) (Tu, 2010; Kang, 2008). The most significant milestones during this phase were the establishment of a complete building energy code system in China, through the issuance of a number of new codes. These include *Design Standard for Energy Efficiency of Residential Buildings in the Hot Summer and Cold Winter Zone (JGJ134)* in 2001[14]; the *Design Standard for Energy Efficiency of Residential Buildings in the Hot Summer and Warm Winter Zone (JGJ75)* in 2003; and the *Design Standard for the Energy Efficiency of Public Buildings (GB50189)* in 2005[15]. In addition to these codes, national standards for energy efficiency of household appliances were issued for the first time in 2005, namely GB12021.2 for refrigerators and GB12021.3 for air conditioners respectively.

Despite the remarkable achievements in policy scope expansion, the shortcomings of the policymaking during this phase were still obvious. The most significant ones might be: 1) given the fact that the codes only targeted to the design stage of buildings, another crucial stage for achieving energy savings in buildings, construction stage, was completely ignored in the established building energy codes system; 2) all the issued building energy codes and national standards for energy

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[14] JGJ134 is the sole serial number of the code. In China, a code (or national standard) is often referred to in terms of the "code serial number" plus "its issuance year" (e.g., JGJ134-2001).

[15] "Public buildings" is a more popular term for "commercial buildings" in China.

efficiency of household appliances were mandatory policy instruments, while the other types (e.g., financial or voluntary instruments) were rarely issued during this period.

2.2.3 The Third Phase (after 2005)

Policymaking efforts for achieving energy savings in buildings have been expedited significantly in China since 2006. This was driven mainly by preparation for the 2008 Beijing Summer Olympic Games (one of its key slogans was Green Olympics), and the Chinese government's commitment to GHG emissions reduction at the Copenhagen Climate Change Conference (COP15) in 2009[16] (Tu, 2010; Kang, 2008).

There were two key milestones in this phase. The first one was the issuance of *Code for Acceptance of Energy Efficient Building Construction (GB50411)* in 2007. With this code, the acceptance of energy efficiency measures in buildings became a prerequisite for buildings' final acceptance at the end of the construction stage (MOHURD and AQSIQ, 2007). Another key milestone was the significant revision of the *Energy Conservation Law of China* in 2008 and the issuance of two follow-up administrative regulations by the State Council in the same year. With these critical legislative documents, the Chinese governments at all levels were officially required to take action to achieve energy savings in the buildings sector.

A number of other policymaking efforts were also implemented after 2005 (Tu, 2010; Kang, 2008), including:

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[16] Reducing the amount of greenhouse gases emitted per unit GDP by 40-45% by 2020 (compared with 2005), in the form of a decision from the Standing Committee of China's State Council (WRI, 2009).

- The revisions on building energy codes were made, such as the issuance of JGJ26-2010, JGJ134-2010, and JGJ75-2012 (the revision of GB50189-2005 is scheduled to be finished by 2015);
- China's green building rating scheme (i.e., 3-Star Scheme) was launched for the first time in 2006;
- Several financial incentives were issued (e.g., the subsidies for retrofitting existing buildings in 2007, subsidies for purchasing energy efficient lamps in 2007, subsidies for purchasing energy efficient household appliances in 2012, multistep electricity pricing in 2012, etc.);
- The national standards of energy efficiency for more household appliances were issued (e.g., clothes washers in 2007, water heaters in 2008, and TVs in 2011, etc.).

2.3 Assessment of Current Energy-Saving Policies for Buildings

The national energy-saving policies for buildings that are currently implemented in China can be grouped into four categories: building energy codes, financial incentives, green building rating schemes, and energy efficiency standards and labelling (EES&L) schemes for household appliances[17] (Zhang and Wang, 2013; TU, 2010, Kang, 2008). A detailed review and assessment on each of them is as follows.

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[17] As shown in Section 2.3.4, the EES&L schemes for appliances in China are actually combined together with the often so-called MEPS (minimum energy performance standard).

2.3.1 Building Energy Codes

2.3.1.1 China's Building Energy Codes

The design of buildings' energy performance in China is guided by delimited five climate zones[18] (AQSIQ and MOHURD, 1993a & 1993b). The five climate zones are the Severe Cold Zone, the Cold Zone, the Hot Summer and Cold Winter (HSCW) Zone, the Hot Summer and Warm Winter (HSWW) Zone, and the Temperate Zone (AQSIQ and MOHURD, 1993a & 1993b). The zoning is mainly based on four climatic parameters - typical "average temperature of the coldest month," "average temperature of the hottest month," "number of days with an average temperature less than 5 °C" and "number of days with an average temperature more than 25 ℃."

To be consistent with its climate zone divisions, China has issued three series of codes for residential buildings in the Severe Cold and Cold Zone, the HSCW Zone and the HSWW Zone respectively (Tu, 2010; Kang, 2008). It also has issued one code for commercial buildings in all the climate zones (MOHURD and AQSIQ, 2005). The entire series of four codes applies only to the "design stage" of new buildings (or the complete retrofitting of existing buildings). In addition, to guarantee the final installation of requested energy-saving measures at a building's construction stage, an "Acceptance Code" was issued in 2007 for the first time (MOHURD and AQSIQ, 2007). Table 2.2 shows a summary of the building energy codes in China.

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[18] The zoning is regulated by two authorization documents - "Thermal Design Code for Civil Buildings (GB50176-93)" and "Standard of Climatic Regionalization for Architecture (GB50178-93)."

Table 2.2 Summary of Building Energy Codes in China

Stage	Building Type		Name of the Code	Code No.	Editions
Design	Residential	Severe Cold Zone & Cold Zone	Design Standards for Energy Efficiency of Residential Buildings in the Severe Cold and Cold Zones	JGJ26	1986, 1995, **2010**
		HSCW Zone	Design Standards for Energy Efficiency of Residential Buildings in the Hot Summer and Cold Winter Zone	JGJ134	2001, **2010**
		HSWW Zone	Design Standards for Energy Efficiency of Residential Buildings in the Hot Summer and Warm Winter Zone	JGJ75	2003, **2012**
	Commercial		Design Standards for the Energy Efficiency of Public Buildings[2]	GB50189	**2005**
Construction	Residential and Commercial		Code for Acceptance of Energy Efficient Building Construction	GB50411	**2007**

(Sources: MOHURD, 1986, 1995, 2001, 2003, 2010a, 2010b, 2012b; MOHURD and AQSIQ, 2005, 2007)

It must be noted that all the building energy codes listed in Table 2.2 are national codes. In China, local governments have the authority to design and implement local codes within their jurisdictions[19] only if they are stricter than the applied national codes.

The building energy code is a fundamental policy instrument for energy savings in buildings since it regulates only the baseline requirements on buildings' energy performance. The enforcement of "building energy codes" is usually either mandatory or voluntary worldwide (ACEEE, 2014b). However, the Chinese building energy codes contain both mandatory and voluntary articles. The mandatory articles must be met, while the voluntary ones are just suggested to be met.

Therefore, the mandatory requirements in China's building energy codes are particularly crucial in shaping the energy performance of new buildings. There are respectively 14, 9 and 13 mandatory articles in the latest editions of code "JGJ26" (for the Severe Cold Zone & Cold Zone), "JGJ134" (for the HSCW Zone), and "JGJ75" (for the HSSW Zone). Generally, these mandatory articles can be grouped into five categories, summarized in Table 2.3.

[19] Some economically developed regions (such as Beijing and Shanghai) have already issued their local building energy codes.

Table 2.3 Classification of Mandatory Articles in Chinese Residential Building Energy Codes

Category	Number of Articles		
	JGJ26-2010	JGJ134-2010	JGJ75-2012
Energy performance of the building envelope[1] and energy efficiency of space heating & cooling systems	7	6	10
Operation of space heating & cooling systems	5	1	1
Use of electricity space heating systems	1	1	0
Protection of ground water sources when adopting ground source heat pumps	1	1	1
Lighting in public areas	0	0	1
Total	**14**	**9**	**13**

Note: [1] Such requirements include a building's architectural features (e.g., building shape factor, window to wall ratio, etc.), heat transfer coefficients of walls, windows, roofs and doors, sunshine shading coefficient of windows, and air-tightness levels of windows and doors.

(Sources: Summarized from MOHURD, 2010a, 2010b, 2012b)

2.3.1.2 Assessment

In this section, the strengths and weaknesses of China's building energy codes system are summarized.

1. Strengths

- **Covering Both Design and Construction Stages**

Before issuance of the "Acceptance Code" in 2007, there was no guarantee to ensure the final compliance of the four codes (namely JGJ26, JGJ134, JGJ75 and GB50189) at the construction stage[20], because they were applied only to the building's design. Consequently, it was common that some code-requested energy-saving measures were not installed during the construction stage due to various reasons (e.g., cost concerns, the weak capacity of contractors, etc.).

This fact can be observed from an MOHURD's code compliance inspection conducted in 2006, which involved about 3,000 buildings. The 2006 inspection showed that the overall code compliance rate of the four codes at the building design stage was as high as 95.7% nationwide, but dramatically decreased to only 53.8% at construction stage (Tu, 2010). This means that only half of the new buildings constructed in 2006 were actually energy efficient (if judging by final code compliance), even though almost all of them were initially designed to be efficient in their energy use.

MOHURD addressed the challenge of low code compliance at the buildings' construction stage by the issuance of *Code for Acceptance of Energy Efficient Building Construction (GB50411)* in 2007. This code made the acceptance of energy-saving measures in a building a mandatory pre-requisite for the building's final acceptance before it would be allowed to be put into operation (MOHURD and

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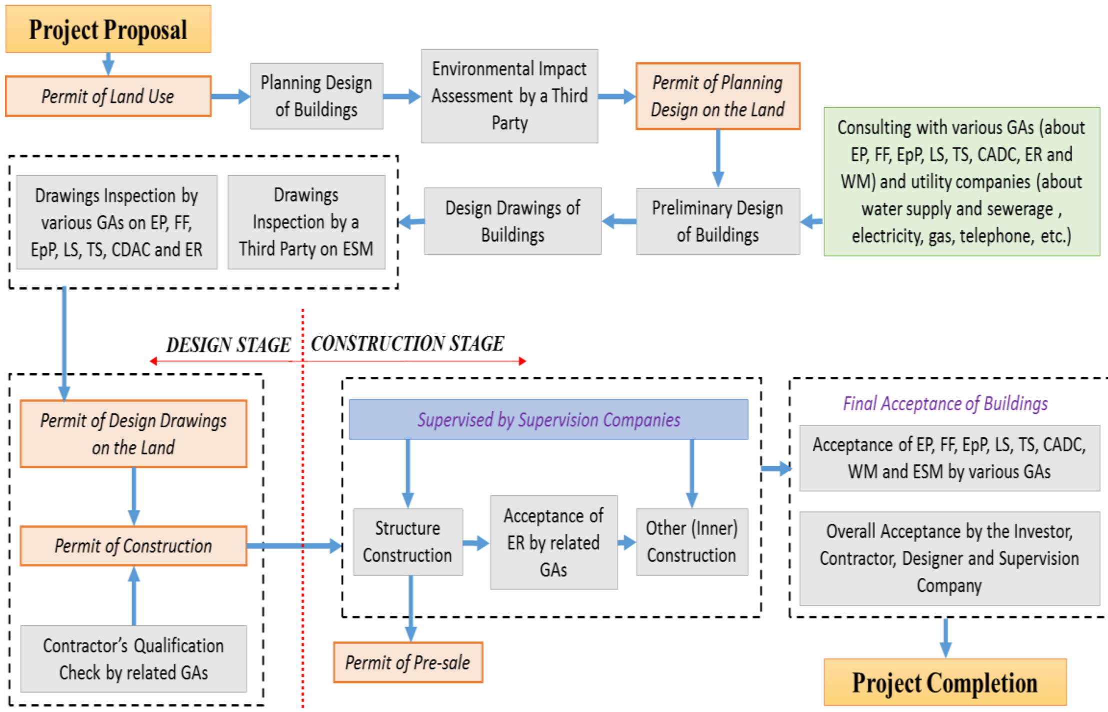
[20] Prior to 2007, the installation of energy-saving measures at the construction stage largely depended on routine checks by supervision companies (hired by property investors as their agents during the construction process); however such routine checks were often impeded in reality (e.g., lobbying from contractors for certain interests). Moreover, not all property development projects involve (or can afford to hire) supervision companies.

AQSIQ, 2007). In other words, the energy-saving measures in buildings were finally given the same importance as other key aspects of buildings (which had long been covered in the final acceptance of buildings), such as fire protection, air defense space, environmental protection, and epidemic prevention.

Through this “Acceptance Code,” the installation of energy-saving measures in buildings was finally completely incorporated into China’s government management system of building development projects. The current process for completing a building development project in China is shown in Figure 2.4[21].

[21] The process may vary in locations, and this figure shows a simplified typical process.



***Note:** EP-Environmental Protection; FF-Fire Fighting, EpP-Epidemic Prevention; LS-Landscaping; TS-Transportation; CDAC-Civil Air Defense Construction; ER-Earthquake Resistant; WM-waste management; ESM-Energy-saving Measures; GAs-Governmental Agencies;*

Figure 2.4 Process of Completing Building Development Projects in China

(Sources: Based on PINC, 2010; MOHURD and AQSIQ, 2007)

Figure 2.4 reveals that the building energy code compliance in China is primarily enforced by two key governance steps: 1) the design drawings inspection of a building by an authorized third party at the end of the design stage - if not passed, the "permit of construction" will not be issued; and 2) the acceptance of energy-saving measures by relevant governmental agencies (usually the local Bureau of Construction) at the end of construction stage - if not passed, the building is not allowed to be put into use. Of the two key governance steps, the latter was established following the issuance of the 2007 Acceptance Code.

The impact of the 2007 Acceptance Code is quite significant, as can be observed from the increasing code compliance rates at the construction stage of buildings since its enforcement (see Table 2.4).

Table 2.4 Compliance of Building Energy Codes in China

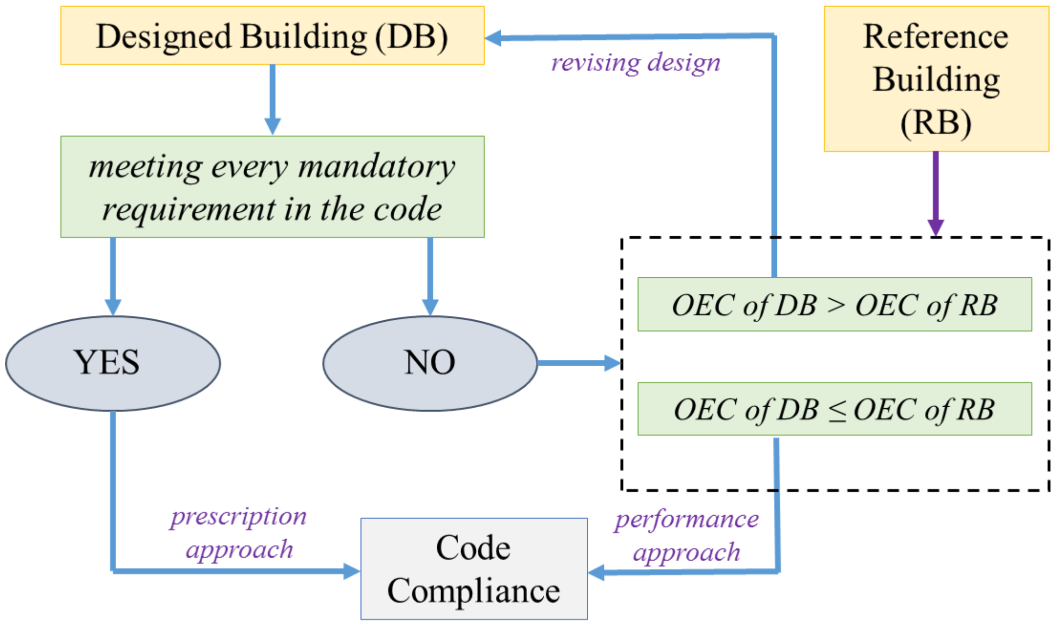
Year	**Compliance Rate at the Design Stage**	**Compliance Rate at the Construction Stage**
2006	95.7%	53.8%
2007	97.0%	71.0%
2008	98.0%	82.0%
2009	99.0%	90.0%
2010	99.5%	95.4%

Note: The compliance involves the codes of JGJ26, JGJ134, JGJ75 and GB50189.

(Sources: Tu, 2010; MOHURD, 2007-2010)

- **Adopting "Dual-Procedure" Mechanism for Code Compliance**

Another important feature of China's building energy code system is the adoption of the "dual-procedure" compliance mechanism for codes JGJ26, JGJ134 and JGJ75. Figure 2.5 shows the "dual-procedure" compliance mechanism.



Note: a) OEC stands for "overall energy consumption" in a whole year; b) A reference building is a virtual building which is identical with the designed building in all architectural features but meeting every mandatory requirement in the applied code.

Figure 2.5 Dual-Procedure Compliance of China's Building Energy Codes

(Sources: Based on MOHURD, 2010a, 2010b, 2012b; MOHURD and AQSIQ, 2005)

From Figure 2.5, it can be seen that there are two optional mechanisms (prescription and performance) for code compliance. If the design of a building meets every mandatory requirement in the applied code, it will be viewed as code compliant. In the case that some of the mandatory requirements are violated, a performance mechanism can then be adopted. For that mechanism, a comparison of the "overall energy consumption (OEC)" for a whole year between the designed building and its "reference building" is made. The "reference building" is a virtual one that is identical to the designed building in all architectural features but that meets every single mandatory requirement in the applied code. If the OEC of the designed building is no more than that of its "reference building," the design building is still viewed as code compliant. Otherwise, some changes need to be made on the designed building to improve its energy performance through another round of code compliance checking.

Through the adoption of "dual-procedure" mechanism for the compliance of China's building energy codes, the building industry in China is given flexibility for building design, which aims at effectively stimulating the application of innovative energy-saving technologies in buildings.

2. Weaknesses

- **Long Code Revision Cycle**

Despite having some strengths, there are also two significant weaknesses related to China's building energy code system. The first one is the lengthy revision cycle process of code, as shown in Table 2.5.

Table 2.5 Revision Cycle of China's Building Energy Codes

Building Energy Code		Revision Cycle
Residential Buildings	Severe Cold and Cold Zones	15 yeas (1995-2010)
	HSCW Zone	9 years (2001-2010)
	HSWW Zone	9 years (2003-2012)
Commercial Buildings		Already 10 years (since 2005)

(Sources: Based on MOHURD, 1995, 2001, 2003, 2010a, 2010b, 2012b; MOHURD and AQSIQ, 2005)

It can be seen that the code revision cycle in China is usually around 10 years or more. As a reference, the code revision cycle in the U.S. (both ASHRAE 90.1 and IECC) takes only three years (DOE, 2013). This long revision cycle in China can significantly impede the timely adoption of emerging energy-saving technologies in buildings. Therefore, the MOHURD should consider shortening the code revision cycle to some extent (e.g., five years as an example) to further expedite energy savings in Chinese buildings.

- **Code Revision Not Institutionalized**

The revision of building energy codes in China is not yet institutionalized. This differs from the practices in the U.S., where codes are revised by the same organizations regularly - ASHRAE 90.1 by the ASHRAE and IECC by the ICC (DOE, 2013),

In China, the MOHURD revised codes primarily based on its perception of the necessity of the revisions. For example, this may be based on the MOHURD-received feedback from academic and industry communities through various seminars, meetings or conferences organized or attended by the MOHURD. Because of the lack of a regular revision mechanism of codes in China (e.g., the issuance of a certain administration rule requiring regular review of codes), the code revision decision in China involves many uncertainties, and is erratic.

Once the MOHURD decides to revise codes, it will start to organize a working team to implement the revision. This working team usually consists of a number of organizations (including academic institutions, building design companies, business companies, etc.). The structure and organization of the revision working team for the same code are often quite different. For example, sixteen organizations were involved in the drafting of the code JGJ26-2010, while, in comparison, only five organizations were involved in drafting its previous edition JGJ26-1995 (MOHURD, 1995 and 2010a).

2.3.2 Financial Incentives

Financial incentives are widely adopted for promoting energy savings in buildings worldwide. According to the World Health Organization (2014), economic instruments can influence people's behaviors through their impact on market signals. This Section introduces and examines China's financial incentives for energy savings in buildings.

2.3.2.1 China's Financial Incentives for Energy Savings in Buildings

In China, financial incentives are usually issued by the Ministry of Finance (MOF), or co-issued by the MOF and other agencies under the State Council (such as the MOHURD or the NDRC - National Development and Reform Commission). Since 2000, financial incentives have been gradually issued in China to facilitate energy savings in buildings. The most significant incentives are introduced below.

1. Funding for New-type Wall Materials

In 2002, the MOF and NDRC co-issued the "Administrative Rules on Fund of New-type Wall Materials"[22] (revised in 2007) (Kang, 2008). According to it, investors of building development projects are subject to fines if their projects do not adopt wall materials with high energy performance (these are called new-type wall materials and

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[22] "New-type wall materials" is a term for the wall materials which have a higher energy performance than the traditionally used clay bricks. The list of them is determined by the Chinese central government, and is updated irregularly.

listed in this administrative rule). The amount of the fine is set by local governments; however it cannot exceed about 1.6 US$/$m^2$ (10 Yuan/m^2; Yuan is Chinese currency) (MOF and NDRC, 2007a). All levied fines go into a local-government managed financial vehicle (called Fund of New-type Wall Materials), and are used to support the research and development (R&D), production and demonstration of wall materials with high energy performance. By implementing this "fines-to-funds" policy, the Chinese government expects to promote the large-scale adoption of wall materials with high energy performance in buildings.

The effectiveness of this economic incentive, however, might be overestimated, since it overlaps with the related requirements in building energy codes. China's building energy codes have stipulated detailed mandatory requirements on the energy performance of walls, and only "new-type" wall materials could meet these requirements. In this sense, given the current high code compliance rate in China, the intervention effects of this economic incentive might be limited.

2. Fiscal Appropriation to the Application of Renewable Energy in Buildings

In 2006, "Administrative Rules on the Specific Fiscal Appropriation to the Application of Renewable Energy in Buildings" (MOF Document No. 459-2006) was co-issued by the MOF and MOHURD (Kang, 2008). According to it, the Chinese central government has the responsibility to annually budget funds to support the application of renewable energy in buildings (MOF and MOHURD, 2006). This includes the adoption of various "Ground Source Heat Pump (GSHP)" systems (e.g., underground water, surface water, sea water, waste water, etc.), and building-integrated solar systems.

To facilitate the implementation of MOF Document No. 459-2006, several follow-up administrative rules were issued by the MOF in 2009, including the "Administrative Rules on the Specific Budget for Subsidies to Applying PV in Buildings" (MOF Document No. 129-2009), "Administrative Rules on the Specific Budget for Subsidies to the Demonstration Cities of Applying Renewable Energy in Buildings" (MOF Document No. 305-2009) and "Administrative Rules on Specific Budget for Subsidies to Applying Renewable Energy in Rural China" (MOF Document No. 306-2009).

According to the MOF Document No. 129-2009 (MOF, 2009a), the Chinese central government would give subsidies to projects using PV in buildings with an installation capacity over 50kWp. The subsidy level is decided annually, and was about 3.2 US$/$W_p$ (20 Yuan/Wp) in 2009, and 2.7 US$/Wp (17 Yuan/Wp) (PV embedded in building materials) or 2.3 US$/Wp (14 Yuan/Wp) (PV installed on walls or roofs) in 2010. Financing priorities are given to the projects of "PV embedded in building materials," "grid-connected PV," and "PV installation in public organizations (such as schools and hospitals)." In the MOF Document No. 305-2009 (MOF, 2009b), selected pilot cities for applying renewable energy in buildings will receive subsidies from the central government (21 cities selected as of 2012), with a cap of 12.9 million US$ (80 million Yuan) for each pilot city. Stipulated in the MOF Document No. 306-2009 (MOF, 2009c), the application of renewable energy in rural China is also subsidized – 9.7 US$/$m^2$ (60 Yuan/m^2) for a water source heat pump (WSHP) and 2.4 US$/$m^2$ (15 Yuan/m^2) for a solar thermal application.

As stated in the "subsidy application scope" of these administrative rules (with the exception of the MOF Document No. 306-2009), these renewable energy subsidy programs, however, target primarily large-scale commercial buildings in cities, but not residential buildings.

3. Subsidies for Retrofitting Existing Buildings

In 2007, the MOF issued the "Administrative Rules on Funding Awards to Retrofit of Existing Buildings in Northern China (Tentative)" (MOF Document No. 957-2007), which covers fifteen provinces (autonomous regions, or municipalities). The funding awards target retrofits of the building envelope and space heating systems (including both indoor and outdoor delivery systems, and boiler plants). The funds awarded by the Chinese central government are distributed to fifteen provinces based mainly on their population and the size of the building stock. Each provincial government manages this subsidy program in its jurisdiction (MOF, 2007). The subsidy level remains the same nationwide, as shown in Table 2.6.

Table 2.6 Subsidies to Retrofits of Existing Buildings in Northern China

Retrofitting Coverage	Severe Cold Zone (US$/$m^2$)	Cold Zone (US$/$m^2$)
Retrofits of Building Envelope	5.3	4.4
Retrofits of Space Heating Systems inside Buildings	2.7	2.2
Retrofits of Space Heating Systems outside Buildings	0.9	0.7
Comprehensive Retrofits (all the above three retrofits)	8.9	7.3

Note: One U.S. dollar is about 6.2 Chinese Yuan (as of July 2015).

(Source: MOF, 2007)

In addition to retrofit existing buildings in southern China, the MOF issued the "Administrative Rules on Funding Awards to Retrofits of Existing Buildings in the HSCW Climate Zone" (MOF Document No. 148-2012) in 2012. In total, twelve provinces or municipalities are covered (e.g., Shanghai, Chongqing). The retrofits include doors and windows, exterior solar shading systems, and insulation of walls and roofs (MOF, 2012a), as shown in Table 2.7.

Table 2.7 Subsidies to Retrofits of Existing Buildings in Southern China (HSCW Zone)

Retrofitting Coverage	**Eastern Region** (US$/$m^2$)	**Central Region** (US$/$m^2$)	**Western Region** (US$/$m^2$)
Retrofits of Doors and Windows	0.7	1.0	1.2
Retrofits of Exterior Sunshine Shading Systems	1.0	1.3	1.6
Retrofits of Insulation of Walls and Roofs	0.7	1.0	1.2
Comprehensive Retrofits (all the above three retrofits)	2.4	3.3	4.0

Note: One U.S. dollar is about 6.2 Chinese Yuan (as of July 2015).

(Source: MOF, 2012a)

4. Subsidies to High-efficiency Lighting Fixtures

In 2007, the "Administrative Rules on Subsidies to High-efficiency Lighting Fixtures" (MOF Document No. 1027-2007) was co-issued by the MOF and NDRC. The high-efficiency lighting fixtures defined in this document include three-band fluorescent lamps (T8 and T5 type), high pressure sodium lamps, metal halide lamps, and LED (Light-Emitting Diodes) lamps (MOF and NDRC, 2007b).

Under this policy, the Chinese central government solicits bids for the lowest price on high-efficiency lighting fixtures among qualified manufacturers (both domestic and international). Then, based on funding levels from the central government, the MOF gives the bid-winning manufacturers a certain amount of subsidy (e.g., this could be 50% of sale price of each lighting fixture sold to households) (MOF and NDRC, 2007b). The primary goal of this subsidy program is to expedite the penetration of high-efficiency lighting fixtures in Chinese households.

5. Subsidies to Energy Efficient Household Appliances

In order to improve the penetration of energy efficient household appliances, the Chinese central government (the NDRC, MOF and MIIT- Ministry of Industry and Information Technology) launched a large-scale subsidy program for energy efficient appliances in 2012[23] - with a total budget of about 4 billion US$ (25.6 billion Yuan). This subsidy program was designed for only one year (from June 2012 to May 2013) (MOF, 2012b).

Through this program, Chinese consumers could receive subsidies for their purchases of qualified household appliances. The subsidy covers five types of popular appliances: air conditioners, refrigerators, TVs, clothes washers and water heaters. The

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[23] Mainly to mitigate the impact of the "2008 global financial crisis" on China, prior to this subsidy program the Chinese governments launched two other subsidy programs for household appliances: 1) the "Appliances to Countryside" program from 2008 to 2011 (13% of retail prices of qualified appliances with caps); and 2) the "New-for-Old" program from June 2009 to May 2010 (10% of retail prices of qualified appliances with caps). However, neither of them focused primarily on the energy efficient aspects of appliances.

implementation of this subsidy program included two steps: 1) the consumers immediately received subsidies from manufacturers at the time of their purchase of qualified appliances; and 2) the manufacturers applied for the return of same subsidy amounts from the central government with proof of their sales records and the copies of purchasers' ID. As of May 2013, about 1.97 billion US$ (12.2 billion Yuan) were paid by the MOF to involved manufacturers in total subsidies (MOF, 2013). Table 2.8 summarizes certain details of this subsidy program.

Table 2.8 Summary of China's 2012-2013 Subsidy Program to Energy Efficient Household Appliances

Appliance Type	**Qualification**	**Subsidy Range** (US$/unit)
Air Conditioners	Fixed-Speed Type with EE Tier-2 and above	29~53
	Variable-Speed Type with EE Tier-2 and above	39-65
Refrigerators	EE Tier-1 only	11~65
Clothes Washers	Top-Loading Type with EE Tier-2 and above	11~32
	Front-Loading Type with EE Tier-1only	42
TVs	PDP Type with an EE Factor 1.4 up	40~65
	LCD Type with an EE Factor 1.7 up	16~65
Water heaters	Gas-fired Type with EE Tier-1 only	32~65
	Solar Type with EE Tier-2 and above	16~89

Note: a) EE stands for energy efficiency; b) The EE tiers of air conditioners, refrigerators, clothes washers, and TVs are respectively stipulated in the national standards of GB12021.3-2010, GB12021.2-2008, GB12021.4-2004, and GB24850-2010; c) The EE tiers of gas-fired and solar type water heaters are respectively stipulated in the national standards of GB 20665-2006 and GB 26969-2011; c) One U.S. dollar is about 6.2 Chinese Yuan (as of July 2015).

(Source: MOF, 2012b)

This subsidy program has received some criticism (TOP10, 2012). First, it was argued that the subsidy level was low, less than 10% of retail prices for qualified appliance products, while it was suggested that the subsidy level needed to be about 20-30% of the products' retail prices to effectively promote the penetration of high-efficiency appliances. This was based on a study on subsidy policies in more than 10 countries.

A second criticism was that higher subsidies go to larger-sized appliance products. For instance, the purchase of a qualified 19-inch LCD TV could receive a subsidy of only 16-24 US$ (100-150 Yuan), while a 42-inch one could receive 56-64 US$ (350-400 Yuan) (MOF, 2012b). As generally a smaller-size product consumes less energy than a larger-size one, the design of subsidy levels in this program, therefore, might be inappropriate for promoting energy savings. Table 2.9 shows the subsidy levels for qualified air conditioners as another example.

Table 2.9 2012-2013 Subsides to Energy Efficient Air Conditioners

Cooling Capacity	**Subsidy** (US$/unit)			
	Fixed-Speed Type		**Viable-Speed Type**	
	EE Tier-1	EE Tier-2	EE Tier-1	EE Tier-2
Less than 4,500W	39	29	48	39
4,500W~7,100W	45	32	55	45
7,100W~14,000W	53	40	65	53

Note: a) EE stands for energy efficiency; b) The EE tiers of air conditioners are stipulated in the national standards of GB12021.3-2010; c) one U.S. dollar is about 6.2 Chinese Yuan (as of July 2015).

(Source: MOF, 2012b)

In addition, it was argued that some appliance types should not be given subsidies. As an example, the PDP (Plasma Display Panel) TV technology has been gradually discarded from the market because of its low competitiveness in both price and energy efficiency, particularly compared to the emerging LED TV technology. Therefore, it is misleading to include both of the two types of TVs into the subsidy program and give them the same level of subsidy.

6. Multistep Electricity Pricing

In order to promote electricity savings in the residential sector and mitigate the fast increasing demand for power generation in the country, the NDRC (2011) issued the "Instructions on Implementing Multistep Electricity Pricing for Households" in 2011. According to this document, each provincial government was required to issue and implement the scheme of "multistep electricity pricing" for households in their jurisdictions as of July 1, 2012. As an example, Table 2.10 shows the old and new schemes of electricity prices for households in two Chinese cities, Beijing and Xiamen. By requiring the mandatory implementation of "multistep electricity pricing" nationwide, the NDRC expects to reduce electricity use in Chinese households.

Table 2.10 Household Electricity Prices in Beijing and Xiamen

City	Old Electricity Prices Schemes (before July 1, 2012) (Yuan/kWh)		New Electricity Prices Schemes[1] (after July 1, 2012) (Yuan/kWh)	
Beijing	0.4883		Tier 1 (<240kWh):	0.4883
			Tier 2 (240~400kWh):	0.5383
			Tier 3 (>400kWh):	0.7883
Xiamen[2]	Tier 1 (<150kWh):	0.4463	Tier 1 (<200kWh):	0.4983[3]
	Tier 2 (150~400kWh):	0.4663	Tier 2 (200~400kWh):	0.5483
	Tier 3 (>400kWh):	0.5663	Tier 3 (>400kWh):	0.7983

Note: [1] The new “multistep electricity pricing” schemes take the calendar year as a calculation cycle; [2] The city of Xiamen lies in Fujian province, which was one of the three pilot provinces in China (along with Sichuan and Zhejiang) for the trial implementation of “multistep electricity pricing” for households since November 1, 2004; [3] The Tier-1 electricity price in Xiamen was 0.4763 Yuan/kWh in the period of one year after July 1, 2012 (called an interim period), and it increased to 0.4983 Yuan/kWh since July 1, 2013.

(Sources: SGBEPC, 2012; XMNN, 2012)

2.3.2.2 Assessment

Based on the introduction of China’s financial incentives for energy savings in buildings, two significant findings can be observed. First, the adopted financial incentives in China are not diversified. Except for the incentive of “multistep electricity pricing,” almost all the other financial incentives are actually subsidy programs. In other words, market-based mechanisms (such as tax incentives, soft loans, etc.) are rarely utilized in China for energy savings in buildings. China’s heavy dependence on subsidy programs as financial incentives may be mainly attributed to two factors: 1) the Chinese governments prefer command-and-control-based policy instruments to market-based ones, possibility due to their long-time experience with a centrally planned economy system; and 2) the lack of adequate institutional capacities (e.g., immature taxation system, banking systems, financial markets, etc.) to implement more complex market-based financial incentives. According to Yang (2013), the capital market barriers to energy efficiency investment in developing countries usually include: 1) potentially high transaction costs in financing energy-efficient technologies; 2) energy efficiency investments are often on a small scale and dispersed, and it can be difficult to quantify the benefits from them (particularly compared to the investment in renewable energy technologies); and 3) many financial institutions are unfamiliar with energy efficiency, and they are reluctant to provide resources for energy efficiency improvements[24].

Moreover, there are few financial incentives targeted to promote energy savings in buildings on a stable and long-term basis. Almost all the subsidy programs mentioned (except for the Fund of New-type Wall Materials) depend on appropriations from the government budget, which makes their administration and enforcement uncertain. For a developing country like China, the primary priorities of government policymaking are usually given to matters related to economic growth, while environmental protection and energy savings are often considered afterwards, particularly in the periods of economic downturn. Therefore, financial incentives that could provide stable and long-term support to residential energy savings and would remove the uncertainties involved in the current subsidy-based programs are much needed in China. Such incentives may include promoting sustainable energy utilities

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[24] Few commercial banks in China have established energy-efficiency financing business line (Tu, 2010).

(SEU) models[25], revolving loan funds, energy efficiency credit from commercial banks, Energy Performance Contracts (EPC) by Energy Service Companies (ESCOs), etc.

2.3.3 Green Building Rating Scheme

The rating scheme of green buildings is a widely used policy instrument for energy savings in buildings[26]. The core concept in green buildings is to lessen a building's negative environmental impacts as much as possible. Accordingly, energy performance is certainly a key concern in the rating schemes of green buildings. By granting rating labels or certifications to qualified buildings, this policy instrument can make building owners (or investors) gain a reputation for their efforts in exploring the harmony between the built environment and nature, thus providing related stakeholders with a moral incentive for energy efficiency.

Currently there are a number of green building rating schemes that have been adopted worldwide. Among the early developed ones are the "Building Research Establishment's Environmental Assessment Method (BREEAM)" of the U.K. in 1990, the "Leadership in Energy and Environmental Design (LEED)" of the U.S. in 1998, and the "Comprehensive Assessment System for Building Environmental Efficiency (CASEBE)" of Japan in 2001 (Reed et al., 2009).

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[25] A SEU is an independent and financially self-sufficient entity responsible for delivering energy efficiency, energy conservation, and customer-sited renewable energy to end users (Byrne et al., 2008).

[26] A "green building" is an environmentally responsible and resource-efficient building (EPA, 2012). It is called a "sustainable" or "high performance" building sometimes.

2.3.3.1 China's Green Building Rating Scheme

The earliest efforts for establishing China's own green building rating scheme can be traced back to the publication of the *Technical Evaluation Manual on Chinese Eco-Homes* in 2001 (revised in 2002 and 2003), which was compiled by several leading academic organizations in China with funding support from the MOHURD. In this manual, the key characteristics of eco-homes in China were explored for the first time. However, this manual has rarely been applied in practice probably because it is just a recommended guideline from the academic community (CSTC, 2010). In 2004, to practice the "Green Olympics" of the 2008 Beijing Olympic Games, the "Evaluation Scheme of Green Olympics Buildings" was issued by the Ministry of Science and Technology (MOST). This evaluation scheme includes over one hundred evaluation items related to the planning, designing, construction and operation of various buildings serving the 2008 Olympic Games (CSTC, 2010).

Based on the above two documents, China's first green building rating scheme was finally launched by the MOHURD in 2006 through the issuance of the national standard *Evaluation Standard for Green Building(GB/T 50378)*. This rating scheme is usually called the 3-Star scheme because it grants three-levels of labels (1-Star, 2-Star and 3-Star labels from low to high) to qualified buildings.

Overall, the evaluation criteria stipulated in GB/T 50378 are too general and too brief, and, as a consequence, make them open to interpretation. In order to facilitate the effective enforcement of the 3-Star scheme, the MOHURD issued additional documents afterwards to further clarify the evaluation criteria, which included the "Technical Instructions for Evaluation Standard for Green Building" in 2007, the "Additional Explanation on Technical Instruction at Building Planning and Design Stage" in 2008, and the "Additional Explanation on Technical Instruction at

Building Operation and Management Stage" in 2009. In short, with continuous policymaking efforts from 2006 to 2009, a practicable green building rating scheme has finally been established in China.

In China's 3-Star rating scheme, qualified buildings are evaluated in six aspects, namely land conservation and outdoor environment (LC&OE), energy conservation (EC), water conservation (WC), materials conservation (MC), indoor environment (IE), and building operation and management (O&M) (AQSIQ and MOHURD, 2006). For each aspect, there are three types of evaluation criteria: mandatory, recommended, and innovative. In total, twenty-seven mandatory, forty recommended and nine innovative criteria are designed for rating residential buildings, as shown in Table 2.11.

Table 2.11 Number of Evaluation Criteria in China's 3-Star Green Building Rating Scheme

Evaluation Aspects	Residential Buildings			Commercial Buildings		
	MC	**RC**	**IC**	**MC**	**RC**	**IC**
LC&OE	8	8	2	5	6	3
EC	3	6	2	5	10	4
WC	5	6	1	5	6	1
MC	2	7	2	2	8	2
IE	5	6	1	6	6	3
O&M	4	7	1	3	7	1
Total	**27**	**40**	**9**	**26**	**43**	**14**

Note: MC, RC and IC stand for Mandatory Criteria, Recommended Criteria and Innovative Criteria respectively.

(Source: AQSIQ and MOHURD, 2006)

The mandatory criteria are the prerequisites for buildings to be qualified for a final rating, namely to become candidate buildings. The final rating of candidate buildings is completely determined by two standards: 1) how many recommended criteria under each of the six evaluation aspects are met, and 2) how many innovative criteria are met in total, as shown in Table 2.12.

Table 2.12 Rating Standards of China's 3-Star Scheme for Residential Buildings

Level of Labels	**Recommended Criteria** (40 items)						**Innovative Criteria** (9 items)
	LC&OE (8 items)	EC (6 items)	WC (6 items)	MC (7 items)	IE (6 items)	O&M (7 items)	
1-Star	4	2	3	3	2	4	0
2-Star	5	3	4	4	3	5	3
3-Star	6	4	5	5	4	6	5

Note: Owing to the diversity of climates in China, some of the evaluation criteria may not be applied to a candidate building in certain climate zones - in these cases, the unapplied evaluation criteria are ignored, and then the required pass number of criteria in this table is decreased according to the scale.

(Source: AQSIQ and MOHURD, 2006)

2.3.3.2 Energy-Related Evaluation Criteria

As mentioned before, the energy performance of buildings is a core evaluation concern in China's 3-Star rating scheme. There are three mandatory, six recommended, and two innovative criteria related to buildings' energy performance (for residential buildings), with the details shown in Table 2.13.

Table 2.13 Energy-Related Evaluation Criteria for Residential Buildings in China's 3-Star Green Building Rating Scheme

Criteria Type	No.	Specific Requirements
Mandatory	4.2.1	The design of the building envelope and HAVC systems must meet the related requirements in applied building energy codes
	4.2.2	When adopting centralized space cooling systems, the energy efficiency of chiller units must meet the related requirements in the current edition of code GB50189
	4.2.3	When adopting centralized space heating or cooling systems, household temperature controlling and metering measures must be installed
Recommended	4.2.4	The building should hold appropriate architectural features, including building shape, orientation, WWR (window wall ratio)
	4.2.5	When adopting centralized space cooling systems, the energy performance of involved pumps and fans should meet the related requirements in the current edition of code GB50189
	4.2.6	When adopting centralized space cooling systems, the energy efficiency of chiller units should be one level higher than the related requirements in the current edition of code GB50189
	4.2.7	Adopting energy efficient lighting fixtures in public areas when day-lighting cannot be utilized
	4.2.8	When adopting centralized space heating or cooling systems, energy recovery systems should be installed
	4.2.9	More than 5% of the energy consumption in buildings should come from renewable energy
Innovative	4.2.10	The energy consumption of space heating and cooling should be less than 80% of the level defined in currently implemented building energy codes
	4.2.11	More than 10% of the energy consumption in buildings should come from renewable energy

(Source: AQSIQ and MOHURD, 2006)

As can be seen in Table 2.13, all the three mandatory criteria focus on related mandatory requirements in applied building energy codes. Of the six recommended criteria, 4.2.4, 4.2.5, 4.2.7 are also about code compliance. Although the recommended criterion 4.2.6 is not a mandatory requirement in the codes, it is usually complied with in practice [27]. In short, only the two recommended criteria 4.2.8 and 4.2.9 can actually be seen as stricter requirements on a building's energy performance from the baseline defined by applied building energy codes.

In reality, few residential buildings in China adopt centralized space cooling systems, so criteria 4.2.5 and 4.2.6 are not applied in most cases. Therefore, it is not difficult for a residential building to achieve a "2-Star" label based on its energy performance as it only needs to pass two easily-achieved recommended criteria (4.2.4 and 4.2.7). Since most residential buildings in southern China do not adopt centralized heating or centralized cooling systems, criteria of 4.2.5, 4.2.6 and 4.2.8 are not applied. In these cases, in order to qualify for a "3-Star" label, only two additional criteria need to be met, which means that a building in southern China that only complies with the two easy criteria of 4.2.4 and 4.2.7 can simply meet the requirements for a "3-Star" label.

This analysis reveals the problems with evaluating buildings' energy performance by China's 3-Star rating scheme. As a consequence of achieving the rating labels easily, the incremental construction cost for buildings to be labeled by

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[27] The residential buildings that adopt centralized space cooling systems represent high-end residential buildings in China, and their investors usually do adopt high-efficiency chillers.

China's 3-Star scheme is actually low[28]. Based on the statistics of 79 rated buildings (42 commercial and 37 residential buildings), the average incremental construction cost is shown in Table 2.14. Given the average housing price in China, about 800-1,600 US$/$m^2$ in most cities (Fang.Com, 2014), the incremental construction costs are only about 3-6% of the housing price.

Table 2.14 Incremental Construction Cost for Achieving China's 3-Star Green Building Labels

Label Level	**Incremental Construction Cost** (US$/$m^2$)	
	Residential Buildings	Commercial Buildings
1-Star Label	9.7	4.8
2-Star Label	19.4	37.1
3-Star Label	48.4	59.7

Note: One U.S. dollar is about 6.2 Chinese Yuan (as of July 2015).

(Source: Schroeder, 2013)

2.3.3.3 Assessment

1. Less Emphasis on Buildings' Energy Performance

As shown in Table 2.11, energy-related evaluation criteria account only for about 15% of the recommended criteria and 22% of the innovative ones, which shows that China's 3-Star rating scheme does not place enough emphasis on energy

[28] Incremental construction cost means the increase in costs as a result of upgrading the energy performance of building envelope.

performance. This can also be observed from an affiliated scoring system of China's 3-Star rating scheme. In the 2007 document "Technical Instructions for Evaluation Standard for Green Building" (MOHURD, 2007), a scoring system was launched for awarding the title of "Pioneer Green Building" to candidate buildings based on their compliance with the recommended evaluation criteria in the scheme. The scoring weights were assigned to all the six evaluation aspects, as shown in Table 2.15.

Table 2.15 Scoring Weights Affiliated in China's 3-Star Green Building Rating Scheme

Building Type	**LC&OE**	**EC**	**WC**	**MC**	**IE**	**O&M**
Residential	0.15	0.25	0.15	0.15	0.20	0.10
Commercial	0.10	0.25	0.15	0.15	0.20	0.15

Note: LC&OE, EC, WC, MC, IE, O&M stand for land conservation and outdoor environment, energy conservation, water conservation, materials conservation, indoor environment, and building operation and management respectively.

(Source: MOHURD, 2007)

The scoring weight for a building's energy performance is only 25% for both residential and commercial buildings. As a point of reference, the U.S. LEED rating scheme, one of the most successful green building rating schemes in the world, gives a much higher weight (about 35% of the total credits) to the energy performance of buildings as part of LEED certification (Reed, 2009).

2. Evaluation Criteria on Energy Performance Can be Further Tighten

The discussion in Section 2.3.3.2 found that it is not difficult for a residential building to achieve a "2-Star" label based on its energy performance as it only needs to pass two easily-achieved recommended criteria (i.e., the criteria 4.2.4 and 4.2.7). This fact reveals that the current evaluation criteria in China's 3-star scheme might be not tight enough.

Functioning mainly as a moral-award policy instrument, gaining a certain level of reputation is often the primary motivation for related stakeholders (e.g., investors or building owners) to apply for the rating. In this sense, the weak criteria in China's 3-Star scheme might be actually an obstacle to stakeholders' motivation on rating application, and then impede the scheme's market penetration. Therefore, to effectively improve the market penetration of China's 3-Star green building rating scheme, tightening its evaluation criteria might help significantly.

2.3.4 Energy Efficiency Standard and Labelling (EES&L) Schemes for Appliances

"Energy Efficiency Standard and Labelling (EES&L)" is a widely adopted practice for promoting the production and consumption of energy efficient appliances, and has been implemented in many countries (e.g., the EU member countries, Thailand, etc.) either voluntarily or mandatorily (Zahran, 2013).

In China, the implementation of EES&L schemes for appliances is mandatory, and merges with the policy instrument of "Minimum Energy Performance Standard (MEPS)" for appliances (Energy Label, 2014). Through this mandatory policy instrument, appliances products with low energy efficiency are prohibited from being sold in the market, and consumers are provided with reliable efficiency information on products to make their purchasing decisions. Moreover, as an information-based policy tool, the EES&L is also particularly important for the implementation of other kinds of energy-saving incentive policies for buildings that need to stipulate certain energy efficiency levels of appliances (e.g., building energy codes, green building rating schemes, subsidy programs for energy efficient appliances, etc.).

2.3.4.1 China's EES&L Schemes for Appliances

China's earliest efforts of establishing its EES&L system can be traced back to 2005 when national standards of energy efficiency were first applied to refrigerators and air conditioners (Energy Label, 2014).

The "legal basis" of China's EES&L system was formed through several important authorization documents, including two national laws (*Energy Conservation Law of China* in 1998 and *Product Quality Law of China* in 2000), one administrative regulation ("Administration Regulation on Certification and Accreditation" in 2003), as well as one national administrative rule ("Administrative Rules on China's Energy Efficiency Label Management" in 2005) (Energy Label, 2014).

Based on these important documents, the "institutional basis" for managing China's EES&L system was established. Three government agencies under the State Council are authorized to develop, enforce and supervise the EES&L schemes for appliances in China - namely the NDRC, the AQSIAQ (General Administration of Quality Supervision, inspection and Quarantine) and the CAA (Certification and Accreditation Administration). The "legal basis" and "institutional basis" of China's EES&L system are shown in Figure 2.6.

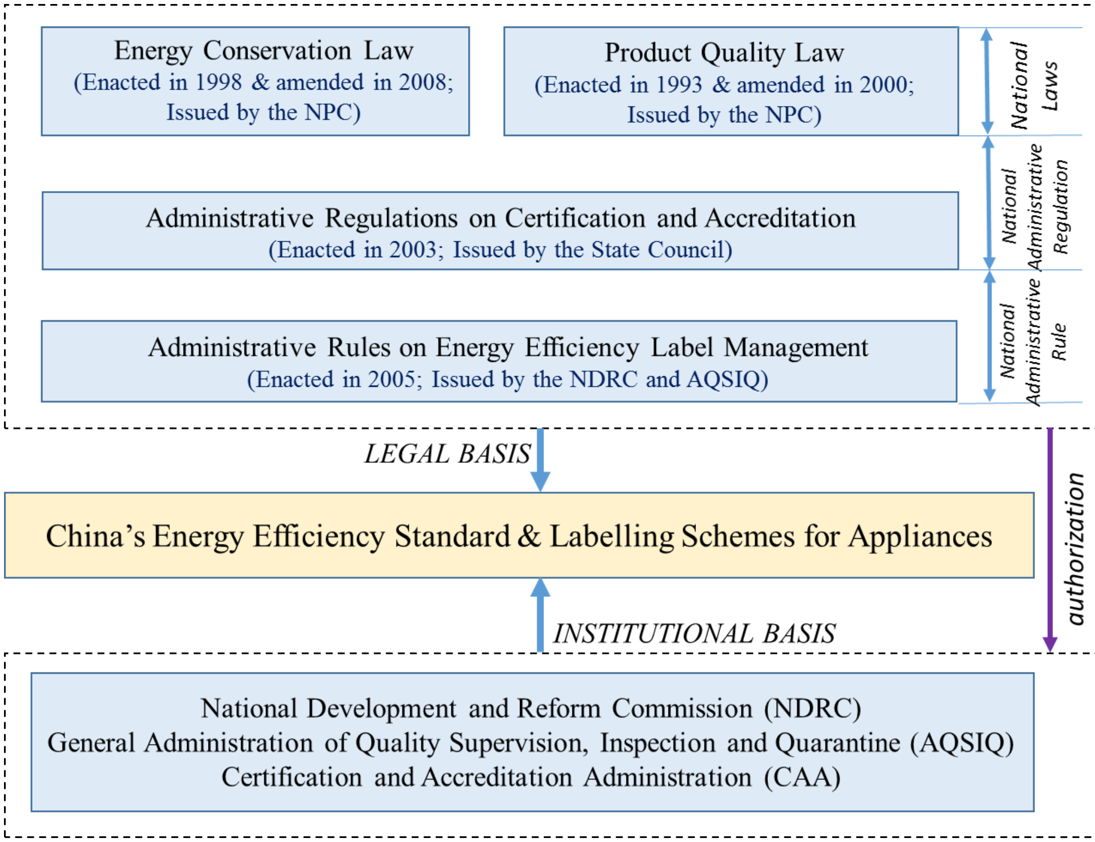

Figure 2.6 Legal and Institutional Basis of China's Energy Efficiency Standard and Labelling (EES&L) Schemes for Appliances

(Source: Based on Energy Label, 2014)

As of February 2015, there were a total of thirty-four kinds of appliances covered in China's EES&L system. Among them, twenty-five kinds are related to energy use in buildings (including residential and commercial), as shown in Table 2.16.

Table 2.16 Household Appliances Covered by China's EES&L Schemes (As of February 2015)

No.	Batch No.	Appliances	Authorization Document	Effected Date	Latest National Standard
1	No.1	Refrigerators	NDRC,AQSIQ & CAA Document No.71-2004	2005.3.1	GB 12021.2-2008
2		Fixed-Speed Room Air Conditioners			GB 12021.3-2010
3	No.2	Clothes Washers	NDRC,AQSIQ & CAA Document No.65-2006	2007.3.1	GB 12021.4-2013
4		Unitary Air Conditioners			GB 19576-2004
5	No.3	Self-ballasted Fluorescent Lamps	NDRC,AQSIQ & CAA Document No.8-2008	2008.6.1	GB 19044-2013
6		Chillers			GB 19577-2004
7		Household Gas-fired Water Heaters			GB 20665-2006
8	No.4	Variable-Speed Room Air Conditioners	NDRC,AQSIQ & CAA Document No.64-2008	2009.3.1	GB 21455-2013
9		Multi-split Type Air Conditioners (heat pump)			GB 21454-2008
10		Electric Water Heaters (with store tank)			GB 21519-2008
11		Induction Cooker			GB 21456-2008
12		PC Displayers			GB 21520-2008
13		Copy Machines			GB 21521-2008

(Continued)

(Continuation of Table 2.16)					
14	No.5	Rice Cookers	NDRC,AQSIQ & CAA Document No.17-2009	2010.3.1	GB 12021.6-2008
15		Electric Fans			GB 12021.9-2008
16	No.6	Ventilation Fans	NDRC,AQSIQ & CAA Document No.3-2010	2010.11.1	GB 19761-2009
17	No.7	Flat Panel TVs	NDRC,AQSIQ & CAA Document No.28-2010	2011.3.1	GB 24850-2013
18		Microwave Ovens			GB 24849-2010
19	No.8	Printers and Fax Machines	NDRC,AQSIQ & CAA Document No.22-2011	2010.1.1	GB 25956-2010
20		Digital TV Receivers			GB 25957-2010
21	No.9	Refrigerated Display Cabinets (with split condensing unit)	NDRC,AQSIQ & CAA Document No.19-2012	2010.1.1	GB 26920-2011
22		Solar Water Heaters			GB 26969-2011
23	No.10	PCs (desktop type)	NDRC,AQSIQ & CAA Document No.39-2012	2013.2.1	GB 28380-2012
24	No.11	Range Hood	NDRC,AQSIQ & CAA Document No.18-2014	2015.1.1	GB 29539-2013
25		Electromagnetic Stoves			GB 21456-2014

(Source: Energy Label, 2014)

China’s EES&L schemes for appliances have designed three or five tiers of energy efficiency (Energy Label, 2014). The lowest energy efficiency tier (usually the Tier-3 for a three-tier scale or Tier-5 for a five-tier scale) means the appliance meets the required minimum energy efficiency level. Products with lower levels of efficiency are prohibited for sale in the Chinese market.

Every unit of covered appliances must have an energy efficiency label on it. Information on each energy label varies among the different kinds of appliances. As an example, Figure 2.7 shows the energy efficiency label for refrigerators in China.

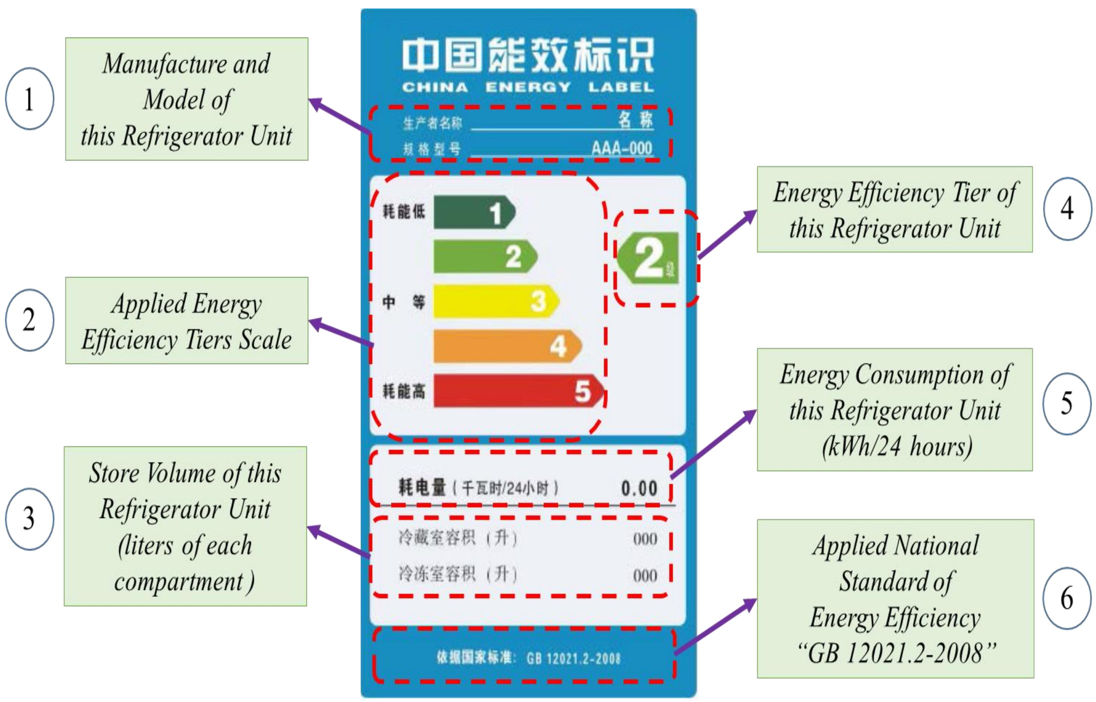

Figure 2.7 Energy Efficiency Label for Refrigerators in China

(Source: Based on CLASP, 2013)

2.3.4.2 Assessment

After ten years of continuous policymaking efforts (begun in 2005) the current coverage of China's EES&L schemes for household appliances is comprehensive. The national standards of energy efficiency for many popularly-owned or energy-intensive home appliances have been issued[29], including refrigerators, air conditioners, TVs, clothes washers, water heaters and rice cookers. Through an empirical experiment in Shanghai on air conditioners and refrigerators, Shen and Saijo (2009) concluded that energy efficiency tiers shown on the energy label have a significant effect on the consumer's purchase choice.

However, some criticism related to the efficiency information presented on China's energy efficiency labels for certain appliances exists. This criticism centers on the fact that the energy information varies significantly among different appliance categories. Table 2.17 reveals this variation.

[29] Some of the national standards of energy efficiency for appliances have been revised: refrigerators in 2008 from 2003 edition, fixed-speed air conditioners in 2010 from 2004 edition, variable-speed air conditioners in 2013 from 2008 edition, TVs in 2013 from 2010 edition, and washing machines in 2013 from 2004 edition.

Table 2.17 Efficiency Information Presented on China's Energy Efficiency Labels for Certain Appliances

Appliances	Efficiency Information Presented on the Label
Refrigerators	Daily electricity consumption (kWh/24 hours)
Fixed-speed Air Conditioners	Energy Efficiency Ratio (W/W)
Variable-speed Air Conditioners	Electric consumption within a cooling season (kWh)
TVs	Energy Efficiency Index (unitless)
PC Monitors	Energy efficiency level (cd/W)
Rice Cookers	Thermal efficiency (%)
Clothes Washers	Electricity consumption per working cycle (kWh/cycle)

(Sources: CLASP, 2013; Energy Label, 2014)

Table 2.17 shows that the efficiency information on the labels for some of the appliances (particularly TVs, PC monitors and fixed-speed air conditioners) requires professional knowledge. The measurement of energy efficiency for these products would be difficult for ordinary consumers to understand. Therefore, this information might not be used effectively when consumers are making a decision to purchase high-efficiency products. For example, the presented efficiency information for TVs is EEI (energy efficiency index), which is a unitless indicator achieved through a specifically designed formula. The EEIs for Tier-1 and Tier-2 LCD (liquid crystal display) TVs stipulated in the national standard GB 24850-2013 are 2.7 and 2.0 respectively. With this information, it is almost impossible for an ordinary consumer to answer the question regarding how much electricity he or she could save by purchasing a Tier-1 LCD TV instead of a Tier-2 one.

In addition, despite the fact that the information for certain kinds of appliances (e.g., refrigerators, variable-speed air conditioners, clothes washers) is easily understood by ordinary consumers, information could still be improved to increase motivation for purchases of high-efficiency units. For example, the CLASP (2013) suggested that the presented efficiency information on the labels of refrigerators should be "kWh/year" instead of "kWh/24 hours;" the TOP10 (2012) further suggested that the products' total energy consumption in their whole lifecycle should be presented on their labels, as this would most effectively facilitate people's decision to purchase high-efficiency appliances units. The U.S. "Energy Guide" label shows another way to encourage consumers' purchase of efficient appliances by presenting estimated yearly operating cost (DOE, 2014). In this way, the energy savings of efficient appliances are presented by their monetary values, which may have a more direct and stronger influences on people's purchase decision.

> *Given desire of policy makers to provide consumers with information to encourage adoption of the lowest energy consuming product (even if this is not necessarily the most efficient) policy makers may wish to consider amending the label declaration to include annual rather than daily energy consumption. The rationale for this proposal is that, at the time to purchase, consumers are considering a range criteria not just related to energy (e.g. price, brand, capacities, etc.). Therefore, performing the annual energy consumption calculation for a number of competing machines may not be at the forefront of their minds. Should they not perform the calculation, then competing machines with 0.4 kWh/24hrs and 0.9 kWh/24hrs may be considered to be relatively similar. However, over a full year, this would make approximately 180 kWh difference in consumption and 90 RMB additional energy cost to the consumer*

(based on electricity costs approximately 0.5RMB/kWh). Therefore, the presentation of annual consumption may have a more significant impact and increase the likelihood of consumers selected the lower energy consumption product (CLASP, 2013: 62-63).

There is also some criticism of the currently implemented EES&L scheme for flat panel TVs (namely GB 24850-2013). Two basic types of flat panel TVs are included in this scheme, namely LCD TV and PDP TV. However, the EEI calculation methods for LCD TVs and PDP TVs are significantly different[30]. Such a difference in EEI's calculation makes the energy efficiency levels between the two types of TVs incomparable, and results in PDP TVs "appearing to be substantially more efficient than is actually the case in comparison with LCD televisions" (CLASP, 2013: 118). In fact, the PDP TVs are much more energy-intensive than LCD TVs on average.

Finally, China's EES&L schemes for appliances are not consistent among appliances as applied in both five-tier and three-tier scales (Energy Label, 2014). According to the author's survey of energy efficiency of appliances in the Chinese market (shown in Table 4.17), Tier-4 and Tier-5 appliance units are rarely available for sale. Therefore, the Chinese central government might consider unifying the various EES&L schemes for the same three-tier scale.

2.4 Chapter Summary

This chapter examined the current energy-saving policies for buildings in China, and provided a critical assessment of them. There are mainly four kinds of

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30 In the calculation, a parameter called "EEI_{ref}" is given 1.1 for LCD TVs, but 0.32 for PDP TVs. There is no any technical explanation provided in the national standard to clarify the difference in "EEI_{ref}" for LCD TVs and PDP TVs.

incentive policies in China: building energy codes, financial incentives, green building rating schemes, and EES&L schemes for household appliances. Among them, building energy codes and EES&L schemes are mandatory.

Through continuous policymaking efforts from 1986 to 2007, China established comprehensive building energy codes system, which includes five codes. Among them, four codes (three for residential buildings in various climate zones and one for commercial buildings) target the design stage of buildings (called Design Codes), while one specifically targets to the construction stage (called Acceptance Code). With the Acceptance Code in 2007, the final installation of energy-saving measures in Chinese buildings has become a pre-requisite (like the requirements for fire protection, etc.). Thanks to this Acceptance Code, the Design Codes compliance rate at a building's construction stage has been significantly improved from 53.8% in 2006 to 95.4% in 2010 (Tu, 2010; MOHURD, 2007-2010). In addition, all of the Design Codes adopt a "dual-procedure" mechanism (both prescription and performance) for compliance, which gives the Chinese building industry more flexibility in the application of innovative energy-saving technologies in buildings.

There are still, however, two obvious defects with China's building energy codes system. The first is the very long revision cycle of codes (usually 10 years or more), which might significantly impede the timely adoption of emerging energy-saving technologies. Another one is that the codes revision is not institutionalized in China, which can be observed from the launch mechanism of code revision initiatives, as well as the structure and organization of working teams for code revisions.

Despite the presence of financial incentives in China for energy savings in buildings, nearly all of them (except for the one of "multistep electricity pricing") are actually subsidy programs. In other words, market-based financial incentives (such as tax incentives, sustainable energy utilities (SEU), revolving loan funds, energy efficiency credit of commercial banks, Energy Performance Certificate by Energy Service Companies, etc.) are hardly utilized in the country. Two possible reasons for this include: 1) the influence of the long-implemented central-planning economic system in China (where the governments prefer command-and-control-based incentives over market-based ones); and 2) China lacks the “institutional capacity” (e.g., mature taxation and banking systems, financial markets) to implement more complex market-based financial incentives. Accordingly, because they are heavily dependent on government budget, the subsidy incentives in China could not commit to promoting energy savings in buildings on a stable and long-term basis.

A green building rating scheme (called the 3-Star scheme) has been implemented in China since 2007. However, this scheme may not contribute much to China’s energy savings in buildings, primarily because of its weak criteria on buildings’ energy performance. The market penetration of this 3-Star rating scheme in China is quite low (only 376 buildings in total received the label from 2006 to 2011[31]) (Schroeder, 2013). As gaining a certain level of reputation from receiving a rating is often the primary motivation for related stakeholders to apply for a building rating, weak criteria might significantly impede stakeholders’ motivation. Therefore, tightening the evaluation criteria of China’s 3-Star scheme is needed. In addition, since energy performance is not emphasized much in the scheme, China may need a special energy-focused building rating (or labelling) system along with its 3-Star green

[31] Including both residential and commercial buildings.

building rating scheme, just like the Energy Performance Certificate (EPC) system currently implemented in Germany (DENA, 2014).

Through continuous policymaking efforts during the past ten years, China currently has established a comprehensive EES&L schemes system for household appliances (e.g., refrigerators, air conditioners, TVs, clothes washers, water heaters, rice cookers). In this mandatory EES&L system, an energy efficiency label must be placed on every applied appliance, and consumers can then make their purchase decision based on the presented energy efficiency (or performance) information on the label. However, the realistic effects of the energy efficiency labels may be significantly impeded by the presented information itself. For example, the efficiency information shown on the labels for some appliances (particularly TVs, PC monitors and fixed-speed air conditioners) is quite difficult for ordinary consumers to understand. Although the efficiency information for some appliances (e.g., refrigerators, variable-speed air-conditioners, clothes washers) is comprehendible to ordinary consumers, it could be further improved (by presenting lifetime energy savings or annually saved energy cost) to better encourage a consumer's decision to purchase efficient appliances.

Chapter 3

METHODOLOGY

This Chapter presents the methodology for this research. As stated in Chapter 1, the two research questions of this dissertation are: 1) how to analyze the residential energy-saving potential in southern Chinese cities; and 2) what information could be revealed from the potential analysis for effective policy interventions? Answering the first question requires a conceptual framework and analytical approach to residential energy-saving potential tailored specifically to southern China. The second question requires that the proposed analytical approaches are able to quantitatively evaluate the real-world impact of various incentive policies on residential energy-savings.

This Chapter comprises five sections. In Section 1, several key concepts related to the analysis of residential energy savings are introduced. These include "rebound effects" and "individuals' decision making" on adopting advanced technical measures. Based on a literature review, Section 2 presents an overall conceptual framework of energy-saving potential analysis, including "technical potential," "economic potential," "maximum achievable potential (MAP)," and "possible achievable potential (PAP)." The specific computational approaches or models for these four kinds of energy-saving potentials are presented in Section 3. As extensive data are required for the potential analysis, Section 4 discusses the methods of data collection. Section 5 summarizes the findings.

3.1 Key Concepts Related to Energy Savings

3.1.1 Strategies of Achieving Residential Energy Savings

Energy savings can be achieved basically through two different strategies: "technological progress" and "behavioral changes[32]." As Kok et al. (2011: 5280) stated, "most policy making efforts to reduce the environmental impact of energy consumption have focused on energy-efficient technology and renewable energy resources. However, changing people's behavior may also significantly reduce energy consumption."

Kok et al. (2011) state that the strategy of "technological progress" involves two aims - namely the improvement of energy efficiency and the application of renewable energy. Energy efficiency improvement usually means using less energy to achieve the same level of energy service; increasing the use of renewable resources (i.e., solar, wind, geothermal) could certainly reduce the related demand for conventional energy resources (i.e., coal, oil and natural gas). Both "technological progress" methods contribute to the reduction of conventional energy consumption.

Analysis of behavioral changes has long been viewed as a critical and attractive research topic for energy savings since the oil shocks of the 1970s, although the understanding on how to (or the drivers to) change people's energy-related behaviors, however, are still debated among researchers (Stephenson et al., 2010; IRGC, 2013).

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[32] The term "behavioral change" has a similar meaning as the one that is often called "lifestyle shifting." In comparison, the concept of lifestyles often means a systems perspective to study consumer behaviors.

It is important to note that "technological progress" and "behavioral changes" are not independent of each other, but are closely linked. On one hand, "technological progress" could cause a change in people's energy use behaviors, either positively or negatively for energy savings. A positive example comes from the research studying the impacts of "information feedback" mechanisms on residential electricity consumption. Research found that the real-time information feedback technology (i.e., an energy use display device installed at home) could result in more residential electricity savings on average than the traditional information feedback mechanism (i.e., electricity billing) (EPRI, 2009). The negative influence which has figured prominently in the criticism directed at "technological progress" mechanisms comes primarily from the usually so-called "rebound effects" along with the adoption of high-efficiency technologies[33]. On the other hand, people's energy-related behaviors usually have a critical influence on their adoption-decisions of advanced technical measures. For example, people who are more concerned about the environment may prefer to purchase smaller-sized or more efficient household appliances. An individuals' concern for environment, however, may decrease after such a purchase.

> *Adoption of new energy efficiency technologies requires consumer acceptance, and thus the other aspect of relevance to policymakers, as they design energy efficiency policies, is to understand how consumer decision-making and behavior affect efficiency investments, considering changes in economic incentives and social as well as psychological processes. It could then be possible to predict how the net effect of these factors will influence the overall amount of energy used (IRGC, 2013: 7).*

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[33] The term "rebound effects" is discussed in detail in Section 3.1.2.

This indicates that two key concepts attached to the link between the two basic energy-saving strategies are the "rebound effects" caused by "technological progress," and "people's adoption-decision" of advanced energy-saving measures (which is a core component of people's energy-related behaviors). Both of the two concepts are critical for analyzing energy savings in the residential buildings sector. Figure 3.1 presents the strategic framework for achieving residential energy savings.

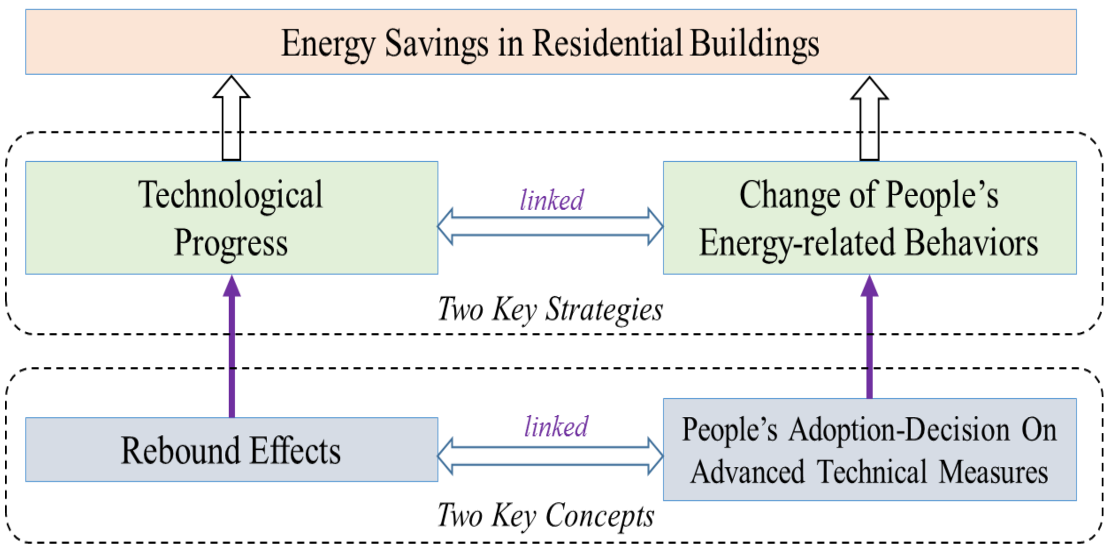

Figure 3.1 Strategies Framework of Achieving Residential Energy Savings

(Sources: Based on Kok et al., 2011; IRGC, 2013)

3.1.2 Rebound Effects

One of the primary goals of energy efficiency policies is to reduce energy consumption[34]. Accordingly, the scale of the energy savings caused by such policies is certainly a critical criterion for their effectiveness. As the energy efficiency improvement of technical measures often involve significant "rebound effects" of energy consumption (IRGC, 2013; ACEEE, 2012; Ouyang et al., 2010), it is very important to consider such effects in the estimates of energy savings, as well as in the design of efficiency policy incentives.

According to the IRGC (2013: 9), there are generally two types of "rebound effects," direct and indirect, as described below:

Direct rebound effects: efficiency gains lead to a lower price of energy services, leading to an expanded or intensified use of the energy-consuming product/service;

Indirect rebound effects: the additional income that is freed up by saving energy costs can be used for other energy consumption.

Specifically for energy consumption in residential buildings, the "direct rebound effects" mean the net changes of energy use cancel out the energy savings from energy-efficiency technology. For example, people may intentionally use a high-efficiency air conditioner longer than they previously did with a low-efficiency one because of lower operation cost. In comparison, the "indirect rebound effects" represent the net changes of energy use in other kinds of energy services due to the

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[34] Other goals may include affordable energy cost, climate change mitigation, etc.

economic savings caused by their residential energy efficiency investment. For instance, the money saved from adopting a high-efficiency air conditioner may be used for another purpose, such as additional family travel. Figure 3.2 summarizes the formation mechanism of rebound effects.

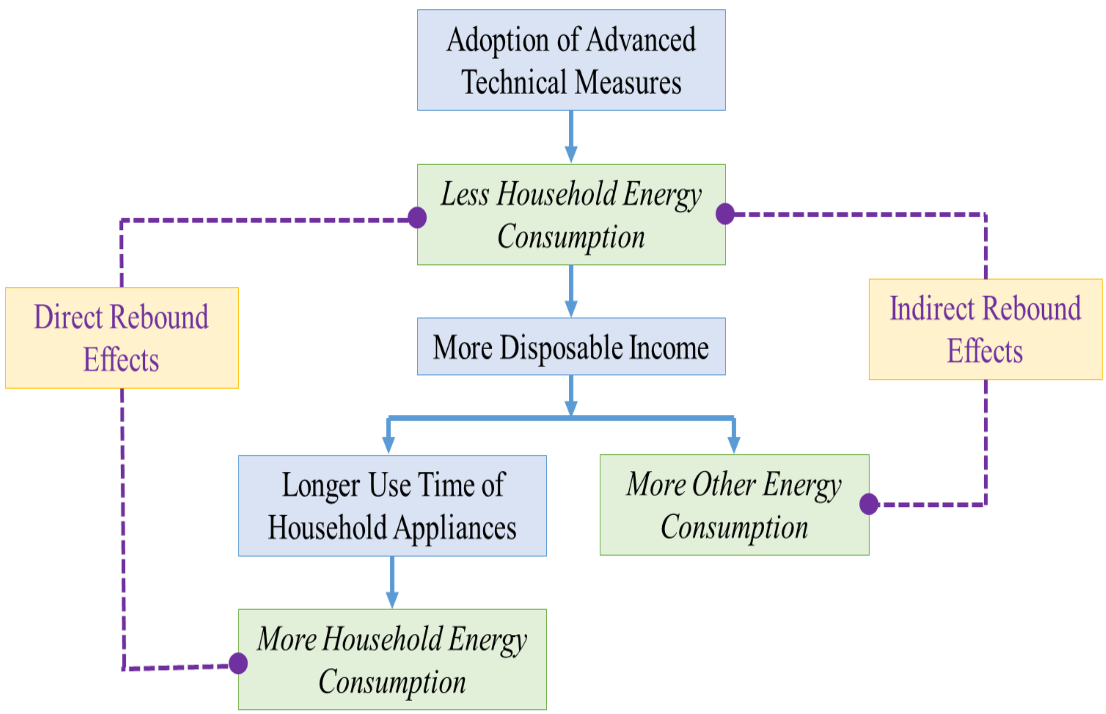

Figure 3.2 Formation Mechanisms of Rebound Effects in Household Energy Consumption

(Source: Based on Ouyang et al., 2010)

Although "rebound effects" seem obvious, estimating them is still rather challenging. According to the IRGC (2013: 9,18), rebound effects are closely related to the concepts of "substitution effects" or "income effects" in economics, which mean that the measurement of "rebound effects" needs to involve the analysis on the efficiency elasticity of demand for energy services[35]. However, such elasticities are difficult to measure owing to the absence of energy service demand data which should be disaggregated over an appropriate timescale. Additionally, usually the variation in efficiency in residential sector is limited (IRGC, 2013).

Indirect rebound effects actually represent economy-wide rebound effects, which are complicated and much more difficult to estimate than direct effects because of the involvement of the substitutability between people's different services (or utility) demands. The IRGC (2013: 5) stated that "how these economic savings are used by the consumers have led to a long debate in the energy economics and energy policy literature." Because it involves many uncertainties, a reliable quantitative analysis on economy-wide rebound effects usually needs a comprehensive and detailed analysis of the substitution and income effects of residents' consuming behaviors through computational general equilibrium (CGE) models[36].

Since this research focuses on residential energy savings, the involvement of "indirect rebound effects" is beyond the targeted scope of this dissertation study. Therefore, only the "direct rebound effects" from various residential energy services

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[35] The efficiency elasticity of demand for energy services means the percentage change in quantity demanded for energy services in response to a one-percent change in efficiency.

[36] These models usually assume non-linear production functions and "focus on the production side of an economy, and how input and output demand relationships between sectors of the economy change as a result of price changes and economic growth" (IRG, 2013: 18).

(e.g., space cooling, lighting, TVs) will be considered in the energy-saving potential analysis of this research.

The scale of "rebound effects" can be expressed in a rebound coefficient "φ" according to the research (Ouyang et al., 2010), which is defined as follows[37]:

$$\varphi = \frac{Calculated\ Savings - Actual\ savings}{Calculated\ Savings} \qquad (3.1)$$

The size estimates of "direct rebound effects" in household energy consumption vary among end-uses and researches. For example, the IRGC (2013) reported that direct rebound effects are about 5-12% for lighting, 0-50% for space cooling, and up to 40% for water heating. However, the ACEEE (2012) reported that the average direct rebound effects in space cooling is about 13%, and it further stated that such effects are inclined to be higher in moderate climates where the use of air conditioning is considered as optional rather than mandatory; it also reported that there is a small amount of rebound in clothes washing (about 5%), but there is little evidence of rebound effects in water heating and refrigerating. By reviewing different studies, the ACCEE (2012) also observed that many estimates of higher rebound effects are primarily based on studies on consumers' response to changes in energy prices, but not to changes in energy efficiency. In summary, the ACEEE (2012) concluded that there are direct rebound effects in household energy use, but these tend to be modest, generally 10% or less.

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[37] A higher coefficient "φ" means a larger direct rebound effect.

Since this dissertation concerns a case study in China, it will be more relevant to review the literature of rebound effects related to China studies. Unfortunately, such studies in China are very rare so far.

> *In China rebound effect has been just recognized in recent years and only a few studies have referred to it, and no study has touched on the rebound effect in the household sector (Ouyang et al., 2010: 5270).*

> *Although there are a growing number of contributions on this topic for China's issues, researchers rarely studied the rebound effect of energy consumption in the residential building sector (especially the studies that take the technological advancement of the building materials and designs into consideration) due to the statistics in China (Lin and Liu, 2015: 9).*

Ouyang et al. (2010) stated that the "rebound effects" in Chinese households may be as high as 30-50%. It must be noted that this scale is just the authors' own arbitrary estimation, which is not based on any empirical studies. In addition, the definition of "rebound effects" in the paper (Ouyang et al., 2010) is much broader, and includes three kinds: 1) direct rebound effects; 2) indirect rebound effects; and 3) effects related to overall household income growth (e.g., more spending which results in more energy use). It can be seen that as the definition of "rebound effects" often varies much among different research, it is always important to make sure that any scale comparisons of "rebound effects" are based on the same concept.

It should be noted that the "indirect rebound effects" are different from the "rebound effects caused by overall household income increase," despite the fact that the underlying rationale for both of them is the so-called "income effects" in economic principles. The “indirect rebound effects” are caused by relatively more disposable income because of saved energy cost, while the above-mentioned third kind of rebound effect is related to people’s overall absolute growth of household income.

In this dissertation, as shown before, the “rebound effects” are defined as the traditional first two kinds (i.e., direct and indirect effects). In contrast, the third kind of “rebound effects” mentioned in Ouyang et al. (2010) paper (which might be more significant than the first two kinds combined in a fast growing economy) is taken into account as an “increasing energy-service-level (IESL)” scenario analysis in this paper. Mainly base on Swisher et al. (1997) research on the conceptual breakdown of energy use, a detailed discussion on the influence of household income growth on demand levels of energy services is presented in Section 4.4.4.4 in Chapter 4.

In addition, it needs to be noted that the assumed “rebound effect” scale of 30-50% in Ouyang et al. paper (2010) covers both the urban and rural households in China. The rebounds effects in high-income households (e.g., urban households) are expected to be much smaller than that of low-income households (e.g., rural households) (Galvin, 2014; ACEEE, 2012). Therefore, it can be estimated that the “direct rebound effects” in China’s urban residential buildings might be much smaller than Ouyang’s estimate, given its involvement of the effects of absolute household income growth and rural households.

This research adopts the size of direct rebound effects from the U.S. research (ACEEE, 2012) in order to examine the energy savings potential in residential buildings in Xiamen: 25% for space cooling, 20% for water heating, 5% for clothes washers, TVs and PCs. As it was found that the direct rebound effects related to food-preparing appliances are very weak (THUBERC, 2013), a rebound coefficient of zero is given for refrigerators, rice cookers and gas cook stoves in this research.

3.1.3 Adoption-Decision of Advanced Technical Measures

Consumption patterns are supported and constrained by complex socio-technical systems (Bengtsson, 2010). Accordingly, the concept related to people's adoption-decision of advanced technical measure has been long explored from quite a wide range of disciplinary perspectives (Stephenson et al., 2010), which can be classified roughly into three main categories: social psychology, economics, and technology adoption theories.

3.1.3.1 Social Psychology Perspective

From social psychology perspective (including its branch of environmental psychology), the core research focuses on the relation of attitude-behavior (Allport, 1935; Oskamp and Schultz, 2005; Stern et al., 1995, 1999; Stern, 2000). Gordon Allport (1935), one of the founders of modern social psychology, pointed out that the concept of attitude is probably the most distinctive concept in contemporary American social psychology. Oskamp and Schultz (2005) stated that attitude is a useful concept since it can conveniently summarize or predict actual behaviors.

In the field of social psychology, many theories or models have examined the factors and mechanisms that influence people's attitudes and behaviors. Among these models, the most fundamental and widely accepted one is the "Theory of Reasoned Action (TRA)" developed by Fishbein and Ajzen's in 1975, which was later revised by Ajzen in 1985 to the "Theory of Planned Behavior (TPB)" (Johnson and Boynton, 2010).

One of the most significant contributions of Fishbein and Ajzen's TRA model is the introduction of a meditating variable of "behavioral intentions" in the relationship between attitudes and behaviors (Oskamp and Schultz, 2005). The TRA model can be expressed as follows (Ajzen, 1991),

$$I = A_B \times w_1 + SN \times w_2 \qquad (3.2)$$

$$A_B = \sum b_i \times e_i \qquad (3.3)$$

$$SN = \sum n_i \times m_i \qquad (3.4)$$

where "I" stands for behavioral intentions; "A_B" stands for a person's own attitude toward the behavior; "SN" means the person's subjective norms about what relevant other people think he or she should do; "w_1" and "w_2" are weights; "b_i" means beliefs about the consequences of performing the behavior; "e_i" means the person's evaluation of that consequences; "n_i" means the beliefs about what each "significant other" thinks the person should do; "m_i" means the person's motivation to comply with that other.

TRA model reveals that an individual's behavioral intention to perform a certain behavior is a weighted additive function of two variables: his/her own attitude and subjective norms about what relevant other people think he/she should do. Further, one's attitude is composed of a series of beliefs (about performing a behavior) of his/her own multiplied by his/her evaluation of the consequences of performing that behavior; similarly, one's subjective norm is composed of a series of normative beliefs (about what other significant people think he/her should do) multiplied by his/her motivation to comply with the expectancy of others (Ajzen, 1991).

In summary, although the TRA model provides a well-established theoretical basis for exploring effective mechanisms to change people's behaviors, significant barriers still exist for applying this model to quantitatively empirical studies on people's behaviors. This situation may be attributed to the fact that "behaviorist portrayal is difficult to verify empirically" (EPRI, 2009: 1-3).

Nonetheless, based on the TRA model, various mechanisms to shape people's attitudes and subjective norms are extensively proposed and studied by researchers. These mechanisms mainly include: 1) direct personal experience through repeated exposure; 2) parental influence; 3) school indoctrination; 4) pressure of peer groups; 5) conformity pressures in general (i.e., the impact of major social events of the era, the overall culture context within which people live); 6) influences from reference groups (i.e., movie stars, musicians); and 7) mass media of communication (i.e., newspaper, magazines, books, movies, radios, televisions, internet, etc.) (Oskamp and Schultz, 2005). In general, all of these proposed TRA model-based mechanisms could function as effective ways to change people's behaviors for achieving energy savings.

3.1.3.2 Behavioral Economics Perspective

Another important perspective that studies people's energy use behavior is economics. The related theories here mainly include "rational choice theory" in microeconomics, and "bounded rationality theory" and "heuristics" in behavioral economics.

According to "rational choice theory," one always seeks the most cost-effective action to achieve a specific goal (Mankiw, 2009). The key assumptions of “rational choice theory” include: 1) all available actions can be compared and then ranked in a complete partial ordering of preference; 2) an individual has full information about the exact outcomes any action choice he/she has made; and 3) an individual has the cognitive ability and time to weigh every action choice against every other choice.

The concept of “rationality” is further developed to “bounded rationality” in behavioral economics which recognizes the fact that an individual’s decision-making (i.e., action choice) is restricted by one’s own limited information, knowledge, ability and even time (Just, 2014). The concept of “bounded rationality” actually revises the idealistic assumption in “rational choice theory” in order to better account for the realistic situations of people’s decision making.

Based on the concept of “bounded rationality,” most behavioral economists adopt the term “heuristic” to explain people’s decision making process (Just, 2014). “Heuristic decision” means that people often focus on an aspect of a complex problem, and then adopt simple and efficient rules to make a decision, which may lead to deviations from the expectation of “rational choice theory.” In the view of behavioral economists, heuristics are not only useful in intuitive decision-making process but also work well for deliberate decision-making process when facing limited information, knowledge and time (Just, 2014).

The concepts of “bounded rationality” and “heuristics” provide a key theoretical basis for understanding people’s real-world adoption-decision of advanced technical measures.

3.1.3.3 Technology Adoption Theories Perspective

Among the various technology adoption theories, the most widely accepted one may be Rogers' "Diffusion of Innovations." Rogers' theory was first proposed in 1962, and has been widely accepted in the academic community deepening people's understanding of "technological progress" in human society. According to Rogers (1995), technological progress represents the diffusion (or adoption) of advanced technologies in human society, and the diffusion is a process "by which an innovation (often a technological innovation) is communicated through certain channels over time among the members of a social system." Roman (2003: 55) stated that Rogers' theory "synthesizes 50 years of diffusion research and distills it into a set of general principles that explain how a new idea or innovation propagates in a social system" and it "stands today as a fertile ground for conceptual and methodological creativity."

Rogers' (1995) theory of "Diffusion of Innovations" is expressed within a process model of "innovation-decision," which includes five stages: 1) knowledge, 2) persuasion, 3) decision, 4) implementation, and 5) confirmation (see Figure 3.3).

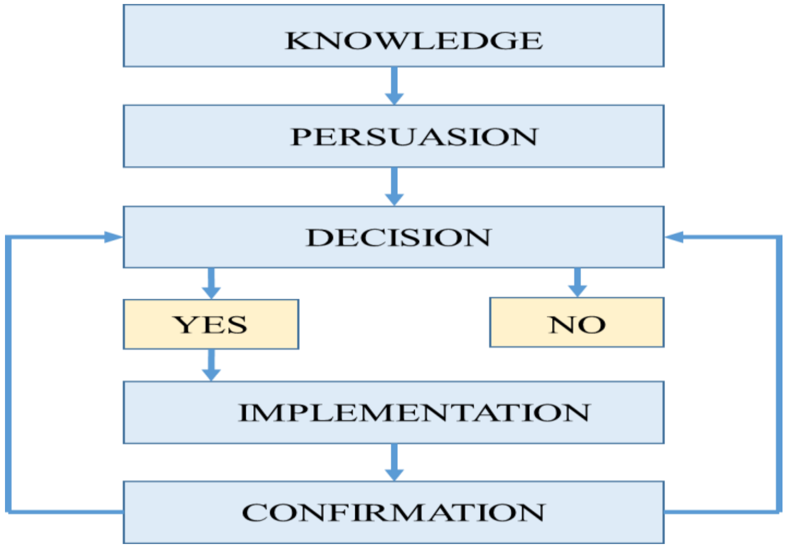

Figure 3.3 Process Model of Rogers' "Diffusion of Innovations" Theory

(Source: Rogers, 1995)

According to Rogers (1995), at the "knowledge" and "persuasion" stages, an individual (or other decision-making unit) mainly seeks the information that helps to reduce the various uncertainties about the cause-effect relationship involved in the innovation's capacity to solve targeted problems. At these two stages, mass media channels and interpersonal communication could effectively provide such information to potential adopters (Rogers, 1995). Specifically, at the "knowledge" stage an individual mainly focuses on the basic information about the innovation (i.e., what the innovation is and how and why it works), and thus mass-media (e.g., newspapers, TV, internet) will be the most rapid and efficient means to meet such needs. At the next stage of "persuasion," one seeks mainly the subjective (rather than objective or scientific) evaluations on the expected effects of innovation adoption from others, and then interpersonal communication starts to become more effective and efficient means of information communication. At the third stage of “decision,” a choice about adopting or rejecting an innovation is made. Once the decision becomes “adoption,” an “implementation” stage follows and the innovation is put into use. At the last stage of “confirmation,” the individual will decide to keep the “adoption” decision previously made, or reverse this “adoption” decision to “rejection” if the perceived message from the innovation’s implementation is not positive enough (Rogers, 1995).

With this process model, Rogers’ diffusion theory clearly shows that even after the implementation of an innovation, a possibility still exists that an individual abandons the innovation adoption. Therefore, besides the information provided in the first two stages, exploring the factors that could reinforce an individual’s decision to “continue adoption” at “confirmation” stage is also critical for technology progress. Such factors can be observed from further analysis of the three key characteristics of innovations which Rogers thought to be crucial in explaining the adoption rate of innovations (Rogers, 1995), namely 1) complexity (degree of difficulty to understand); 2) relative advantages (mainly measured in economic terms and social prestige); and 3) compatibility (i.e., compatible with existing values, past experience, and needs of potential adopters).

After the “decision” stage, the nature of an innovation is already a “known thing” for potential adopters. Therefore, the “complexity” characteristic of an innovation has already been determined by the “decision” stage. According to Rogers (1995), the “compatibility” of an innovation is very likely to be influenced by changing people’s current unfavorable social norms (i.e., values, attitudes, habits) to be compatible with the adoption of expected innovations through certain programs (i.e., education, training and capacity building), which will be a relatively slow process and may not bring actual results in the short term. Consequently, strengthening the "relative advantages" of innovations becomes the fast way to improve the innovation adoption rate at the stage of "confirmation." In Rogers' (1995) definition, the "relative advantages" of an innovation are mainly about its cost-effectiveness and the possible rise of social prestige of its adopters. In this sense, financial and moral incentives could be a very effective means of reinforcing the "relative advantages" of an innovation.

In summary, Roger's theory of "Diffusion of Innovations" provides a solid basis for understanding the key means of facilitating "technological progress" within a social-economic system. Based on Rogers' (1995) diffusion theory, it can be found that three mechanisms are actually quite critical for people's adoption of technological innovations: 1) providing people with necessary information through appropriate communication channels (mass media and interpersonal communication); 2) changing current unfavorable social norms (i.e., values, attitudes, etc.) to be compatible with the adoption of innovations; and 3) issuing effective financial and moral incentives.

3.1.3.4 A Synthetic Adoption-Decision Model

Given the complexity of people's energy use behaviors, the research practices from different disciplinary perspectives (social psychology, behavioral economics and technology diffusion theory) enrich our understanding on the mechanisms of people's adoption-decision of advanced technical measures. Table 3.2 summarizes the main theories from these different research perspectives. In other words, a credible model of "adoption-decision" should be able to incorporate the important theories and concepts listed in Table 3.1.

Table 3.1 Main Theories Related to People's Adoption-Decision of Advanced Technical Measures

Disciplinary Perspectives	**Main Theories**	**Proposed Key Suggestions**
Social Psychology	Fishbein and Ajzen's "Theory of Reasoned Action"	1) People's behaviors are strongly mediated by their behavioral intentions; 2) People's behavioral intentions are shaped by their attitudes and subjective norms about what relevant others think they should do; 3) Various mechanisms are viewed as useful to the change of people's attitudes and subjective norms, including parental influence, school indoctrination, pressure of peer groups, influences from reference groups (i.e., movie stars, musicians); mass media of communication, etc.
Behavioral Economics	"Bounded Rationality" and "Heuristic Decision"	1) People's "rationality" is inevitably restricted by limited information, knowledge, ability and even time which they have; 2) Owing to "bounded rationality," people often focus on an aspect of a complex problem, and adopt simple and efficient rules to make decisions.
Technology Adoption Theories	Rogers' "Diffusion of Innovations"	1) Providing people with necessary information through appropriate communication channels; 2) Changing unfavorable social norms (e.g., values, attitudes) to be compatible with the adoption of innovations; 3) Issuing effective financial and moral incentives.

(Sources: Summarized from Ajzen, 1991; Just, 2014; Rogers, 1995)

Kastovich (1982) developed a computational model of "adoption-decision," which could be used for policy analysis. In his research "Advanced Electric Heat Pump Market and Business Analysis," he concluded that:

When the decision maker chooses a heating/cooling system from alternatives of varying efficiencies and costs the evaluation is based on an analysis of simple payback, i.e., the amount of time needed to recover initial system costs (Kastovich, 1982: 51).

According to Kastovich (1982), people's adoption decision of advanced technical measures can be viewed as a declining curve, in which individuals' adoption rate of efficiency measures increases along with perceived decrease of the "payback time," as shown in Figure 3.4.

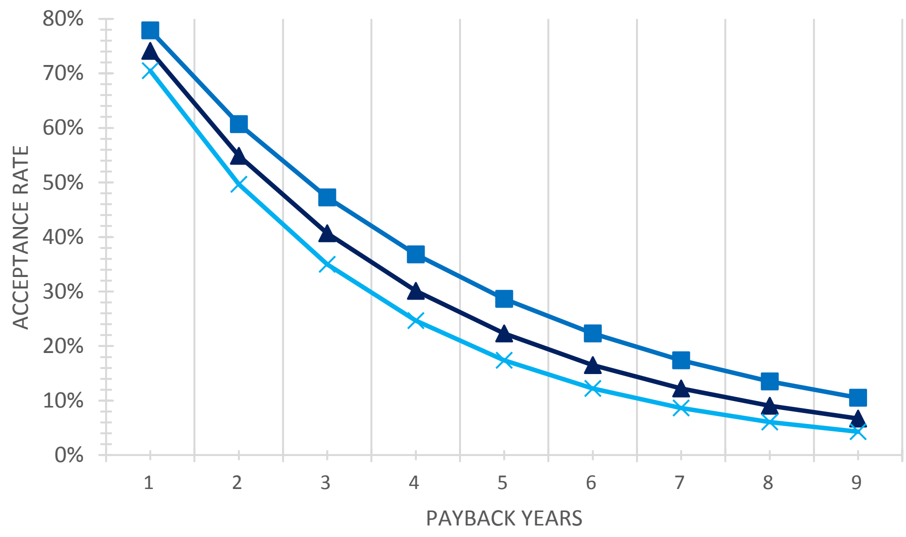

Figure 3.4 Kastovich-Type Adoption-Decision Model of Advanced Technical Measures

(Source: Kastovich, 1982)

This model accords with the fundamental concepts in behavioral economics (i.e., bounded rationality and heuristic decision) through computing people's "adoption rate" of advanced technical measures solely based on a key factor of the "payback time" of the measures.

This model can also reflect the research findings on people's adoption decision in the fields of social psychology and technology adoption (i.e., Fishbein and Ajzen's "Theory of Reasoned Action" and Rogers' theory of "Diffusion of Innovations"). Specifically, from Figure 3.4 it can be seen that the steeper (i.e., with bigger absolute values of slopes) or the higher the position of the curve, the larger is the adoption rate under the same "payback years." In this sense, the steepness and position of the curve could represent a certain level of people's attitudes and subjective norms to targeted advanced measures. Therefore, making people have more favorably related attitudes and subjective norms could shift this curve steeper or higher, which means that the adoption rate of a measure would become higher with the same payback year.

On the other hand, under a certain level of existing social norms and people's attitudes (namely the position and slope of the curve is fixed), financial incentives could effectively improve the adoption rate of the same measure through changing its actual payback time to consumers. Accordingly, various mechanisms suggested by the social psychology and technology adoption research, such as providing required information through appropriate channels, education and training programs, demonstration projects, moral and financial incentives and so on, could be used to shift this declining curve steeper or higher.

In summary, the above-introduced adoption-decision model synthesizes the key concepts or research findings related to people's energy use behaviors from various disciplinary perspectives (i.e., social psychology, behavioral economics and technology adoption theories).

This Kastovich-type adoption-decision model has been used in the U.S. widely for the adoption analysis of both energy efficiency and renewable energy measures. For example, it was adopted in the NREL's research (2010) of "Modeling the U.S. Rooftop Photovoltaics Market" for analyzing people's purchasing decision on PV panels, and the EIA's NEMS (National Energy Modeling System) for portraying people's adoption decision on advanced household appliances (EIA, 2013).

According to R. W. Beck (2009), this Kastovich-type adoption-decision model can be expressed mathematically as:

$$AR = e^{-\alpha \times SPBT} \qquad (3.5)$$

where "*AR*" and "*SPBT*" respectively stand for the "adoption rate" of consumers to advanced technical measures and the "simple payback time" of these measures; "α" is a unitless shape parameter (meaning the adoption rate's sensitivity to the perceived payback time).

Although this type of adoption decision model has been widely used, the value of the shape parameter "α" (which determines the shape and position of the curve) varies among different research. R. W. Beck (2009) surveyed several studies on such models (including the earlier study by Kastovich in 1982), and concluded that the proposed average value of "α" was about 0.3.

According to the EIA's (2013) NEMS, the "simple payback time (SPBT)" of an advanced technical measure can be calculated as:

$$SPBT = \frac{IC - GI}{ECS + PBI} \qquad (3.6)$$

where "*IC*" , "*GI*", "*ECS*" and "*PBI*" respectively stand for the incremental cost between a reference technical measure and an advanced one, government financial incentives (i.e., tax rebates, tax credits, subsidies, etc.) to the advanced technical measure, annual energy cost savings caused by adopting the advanced measure, and annual performance-based incentives to the advanced measure.

In this research, Equations 3.5-3.6 are utilized to calculate the adoption rates of advanced technical measures for Xiamen's residential buildings.

3.2 Conceptual Framework of Energy-Saving Potential Analysis

To analyze the residential energy-saving potential, defining a clear conceptual framework of energy-saving potential analysis is critical.

Much research has been done about the energy-saving potential analysis of the buildings sector. However, the analytical approaches of energy-saving potential for buildings vary among different research. In studies (Dronkelaar et al., 2014; Chung and Rhee, 2014; Xiao et al., 2014; Mata et al., 2013; Paiho et al., 2013; Yu and Chow, 2007; Pfeiffer et al., 2005), the energy-saving potential in buildings was calculated based on the efficiency gap between current adopted technical measures and expected future measures (which were decided either by related best practices or only by authors' specific assumptions). Pantong et al. (2011) estimated energy-saving potential by first assuming expected energy saving policies or programs, and then calculated the potential under certain policy cases. Kuusk et al. (2014), Ouyang et al. (2009) and ACEEE (2008a) particularly emphasized the cost-effectiveness of energy-saving potential (quoted below). In the study by Dall'O' et al. (2012), the potential analysis was implemented in a combined way, including technical, legal, and economic points of view.

> *"As a result, accurate calculations of each measure's initial and relative maintenance costs and their overall final financial benefits, using the simplified LCC method, will likely decide whether they will be implemented or not in the energy-saving renovations (Ouyang et al., 2009: 145)."*

Given the fact that energy potential analysis is closely related to certain "boundary conditions," it is important and necessary to define a clear conceptual framework with which the energy-saving potential analysis proceeds.

Plenty of research related to energy-saving potential has been done, and the U.S. EPA's *2007 Guide for Conducting Energy Efficiency Potential Studies* (hereafter referred to as the EPA Guide) provides a distinct conceptual framework for analyzing energy-saving potential. By taking the view of efficiency as the supply-side alternative, the EPA Guide divided the energy-saving potential coming from energy efficiency improvements into four categories: technical potential, economic potential, achievable potential, and program potential (EPA, 2007).

In the EPA Guide (EPA, 2007), technical potential was defined as "the theoretical maximum amount of energy use that could be displaced by efficiency, disregarding all non-engineering constraints such as cost-effectiveness and the willingness of end-users to adopt the efficiency measures;" economic potential referred to the "subset of the technical potential that is economically cost-effective as compared to conventional supply-side energy resources;" achievable potential meant "the amount of energy use that efficiency can realistically be expected to displace assuming the most aggressive program scenario possible;" and program potential referred to "the efficiency potential possible given specific program funding levels and designs."

Of these four categories, the concepts of "technical potential" and "economic potential" in the EPA Guide are straightforward. Both of them assume immediate and full replacement of existing measures by advanced energy-saving measures (EPA, 2007). Therefore, they represent a kind of static maximum theoretical potential analysis from the current baseline level. These two kinds of potential analysis accounted for the vast majority of potential studies according to the authors' literature review. In comparison, the calculation for "achievable potential" or "program potential" specifically needs to consider the realistic gradual adoption process of advanced technical measures, and then becomes a kind of dynamic calculation of potential within a certain time horizon.

As opposed to "technical potential" and "economic potential," the EPA's concepts of "achievable potential" and "program potential" are relatively loosely defined. The EPA (2007) suggests that the potential coming from "providing end-users with payments for the entire incremental cost of more efficiency equipment" can be called "achievable potential." Given this explanation, the key which differentiates "achievable potential" and "program potential" lies in the strength of incentive policies assumed in the different scenarios. Therefore, "achievable potential" can be referred to as "maximum achievable potential," while the "program potential" as "achievable potential."

Therefore, to avoid confusion in the difference between "achievable potential" and "program potential," which are terms found in the EPA's Guide, a modified conceptual framework for residential energy-saving potential analysis is adopted in this dissertation[38], as shown in Figure 3.5.

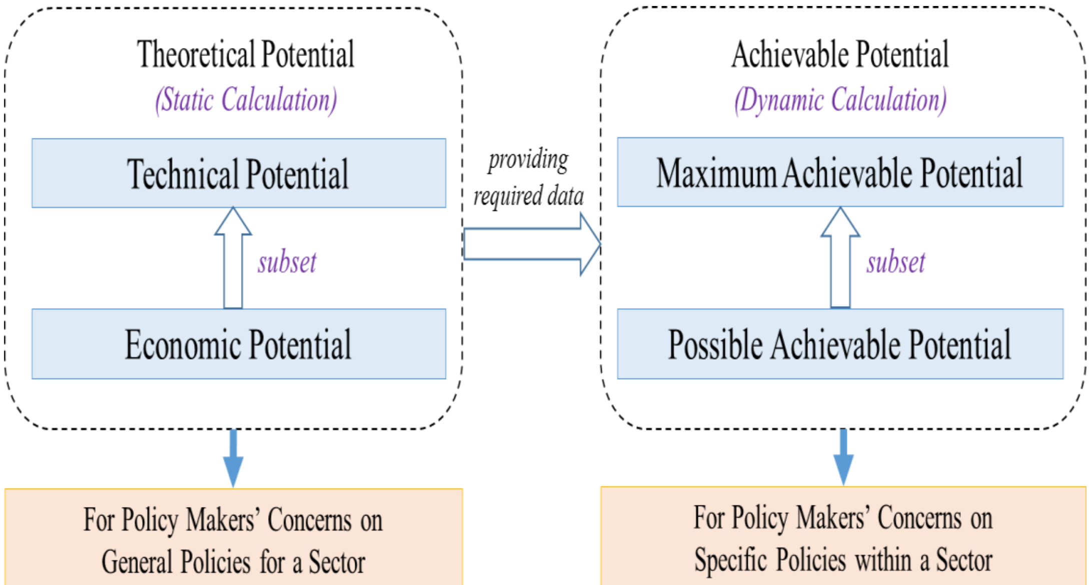

Figure 3.5 Conceptual Framework for Analyzing Energy-Saving Potential in Residential Buildings

(Source: Modified from EPA, 2007)

In this new conceptual framework, the residential energy-saving potential is divided into two streams: theoretical potential (involving static calculation) and achievable potential (involving dynamic calculation). The theoretical potential

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[38] Although the EPA's conceptual framework targets only energy efficiency potential, it obviously also applies to a broader scope, energy-saving potential, which may include energy efficiency improvements, renewable energy applications and changes in people's energy use behaviors.

includes “technical potential” and “economic potential.” Both assume “complete” and “immediate” replacement of existing measures by advanced technical measures, as they are defined in the EPA Guide.

The calculation of technical or economic potential is idealistic, however, the adoption of advanced technical measures in the real world is hardly “complete” and “immediate.” Consider the air conditioners (ACs) in the residential sector as an example: every year only the new purchases of ACs provide the potential opportunities for the adoption of high-efficiency ACs. The annual new purchases come only from two demand sources: the demand of replacing the ACs which reach the end of their useful lifetime (i.e., retirements), and the demand of new added ACs due to population or income growth (i.e., additions).

In reality, the replacement of existing energy use equipment by advanced ones is definitely a “gradual ramping-up” process. Accordingly, achievable potential is certainly a dynamic process that considers the “retirements” and “additions” of technical measures (compared with the ideal assumption of “complete” replacement at a point in time) within a certain time horizon (compared with the ideal assumption of “immediate” replacement). Therefore, as the basic boundary conditions, a specific time horizon (namely the study period), and certain policy cases (given their significant influences on people’s adoption decisions of advanced equipment) must be considered for the analyses of achievable energy-saving potential.

As shown in Figure 3.5, the achievable potential analyses can be further divided into two kinds: “maximum achievable potential” (MAP) and “possible achievable potential” (PAP). The former assumes that only the best or most efficient option of available advanced measures is adopted in the “gradual ramping-up” process, while the latter considers people's realistic adoption decisions among multiple available options of advanced measures.

Based on the EPA Guide (EPA, 2007) and the above arguments, the specific concepts of the four categories of energy-saving potential adopted in this research are summarized below:

Technical Potential: *theoretical maximum amount of energy savings achieved through assuming immediate and complete replacement of existing technical measures by the available best or most efficient measures which are technically feasible;*

Economic Potential: *theoretical maximum amount of energy savings achieved through assuming immediate and complete replacement of existing technical measures by the available energy efficient measures which are not only technically feasible but also cost-effective (the cost-effectiveness of an advanced measure is decided by comparing its "levelized cost of conserved energy (LCOCE)" with the actual cost of saved energy, which is discussed in detail in Section 3.3.2);*

Maximum Achievable Potential (MAP): *the amount of energy savings achieved within a certain time horizon[39] through "gradual ramping-up" replacement process of existing technical measures by the available best or most efficient measures (with the term "gradual ramping-up" replacement process it assumes that only the realistic retirements and additions provide the opportunities for the adoption of advanced measures);*

[39] The length of "time horizon" is decided by the purpose of a research.

<u>Possible Achievable Potential (PAP):</u> *the amount of energy savings achieved within a certain time horizon through "gradual ramping-up" replacement process of existing technical measures and considering people's realistic decisions among available efficient measures under certain incentive policy interventions (people's realistic decisions among available efficient measures in this research are decided by the adoption-decision model defined in Equations 3.5-3.6).*

All the four categories of potential analysis could provide valuable information to policymakers, and different analysis serves different policymaking needs. Generally, technical and economic potential studies provide overall information on energy-saving potential in a static way, which could help policymakers to design general energy policies for a sector or market segment (e.g., residential or commercial sector). In comparison, achievable potential studies could provide detailed information of incentive policies' impact on energy savings in a dynamic way, which could help policymakers to design specific and effective incentive policies (or programs) within a certain sector or market segment. By linking specific incentive policies with the scale of residential energy savings, the "achievable potential" analyses are much significant and informative to policymakers. However, they need extensive data.

In Section 3.3, analytical (or computational) approaches for the four categories of energy-saving potential analysis in southern Chinese residential buildings are discussed in detail.

3.3 Analytical Approaches of Energy-Saving Potential

3.3.1 Technical Potential

As shown previously, the technical potential of residential energy savings can be achieved from two means: energy efficiency improvements and renewable energy application.

In Chinese urban residential buildings, solar water heating and ground source heat pump (GSHP) are the most popular on-site renewable energy applications[40]. Owing to limited building roof space, which is primarily attributed to the dominance of high-rise apartment buildings (often over 10 floors) in urban China, the extensive application of solar water heaters is largely restricted. In addition, the application of GSHP heavily depends on certain geographic conditions. As most Chinese cities face a serious water shortage and their ground water levels are fast descending, the application of GSHP are also significantly restricted.

Given the above-mentioned restrictions, the on-site application of renewable energy resources in Chinese urban residential buildings is expected to be limited[41]. As a result, the energy-saving potential analyses in this research focus exclusively on energy efficiency improvements.

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[40] The application of photovoltaics (PV) in Chinese urban residential buildings is largely restricted by various factors, such as limited roof space owing to the dominant stock of high-rise apartment buildings, low electric price, no net metering incentives, and property management companies' restriction on building roof use.

[41] These restrictions do not impede the off-site application of renewable energy for urban China. In fact, developing large-scale PV plants for power generation has been viewed by the Chinese central government as the most appropriate mean to promoting PV application in the country (NDRC, 2007).

In fact, even in the developed countries such as the U.S. where detached or attached houses account for the vast majority of residential buildings and are thus much more appropriate for the on-site application of renewable energy (e.g., photovoltaics, solar water heating, and GSHP) than is typical Chinese housing, the most significant intervention strategy for energy savings is still energy efficiency improvements. The ACEEE (2014a: 14) stated that in the U.S. "over the more recent period of 2007-2012, savings from energy efficiency programs and policies and warmer winter weather appear to be the most important contributors to declining electricity use" and " these effects were statistically significant for the residential/commercial sectors."

According to the definition of technical potential given in Section 3.2 as well as referring to Swisher et al. (1997), the general calculation principles of technical potential can be expressed mathematically as follows:

$$EEG_i = f\left(EEL_{(i,new\_h)}, EEL_{(i,old)}\right) \qquad (3.7)$$

$$ESP_i = OS_i \times UEC_{(i,cur)} \times EEG_i \qquad (3.8)$$

$$ESP = \sum_{i=1}^{n} ESP_i / \sum_{i=1}^{n} [OS_i \times UEC_{(i,cur)}] \qquad (3.9)$$

where the subscript "*i*" stands for a certain energy end-use equipment; "$EEL_{(i\ old)}$" and "$EEL_{(i,\ new\_h)}$" respectively stand for energy efficiency (efficacy) levels of the existing measure and its relevant highest-efficiency measure for the equipment "*i*" (noting that the indictor selection of "*EEL*" vary among equipment); "EEG_i" stands for the energy efficiency gap between the two "*EEL*" for the equipment "*i*" (expressed in the form of improved percentage from the current energy consumption level); "ESP_i" stands for the energy savings (unit: megajoules) achieved from adopting the highest-efficiency measure for the equipment "i"; "OS_i" denotes the average ownership of the equipment "i" (measured in units per household); "$UEC_{(i, cur)}$" means the "Unit Energy Consumption[42]" of the existing measure for the equipment "i" (unit: megajoules/unit ·year); "ESP" stand for the total technical potential of energy savings (expressed in the form of a reduction percentage from current energy consumption level[43]) from all the involved energy end-use equipment; "n" stands for the total number of involved energy end-use equipment.

It needs to be noted that Equations 3.7-3.9 present only the general calculation principles for technical potential. In practice, the calculation of technical potential is often rather complicated for several reasons:

- the selection of feasible technical measures should be based on a comprehensive understanding and analysis of current residential energy use patterns (namely baseline patterns), which is often hard to be achieved in developing countries because of data availability;
- the EEL indictors of feasible technical measures vary and their selection is often restricted by the availability of related data;

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[42] The calculation of UEC varies among measures, and can refer to the NREL's (2012) document "A Tool to Prioritize Energy Efficiency Investments", as well as the EIA's (2013) "Residential Demand Module of National Energy Modeling System."

[43] In this research, the calculated energy-saving potential is presented in the form of a reduction percentage, which is more perceptible for readers than being presented in the form of absolute amount.

- the "interlinked impacts" of different technical measures need to be carefully considered (e.g., the interlinked impact between the retrofitting measures of building envelope and efficient air conditioning systems);
- there are uncertainties related to the "replacement effects" among different types of appliances (e.g., there are two basic types of clothes washers in China which have significant difference in energy efficiency, top-loading and front-loading types, and both of the two types account for a certain market share).

As shown in Equations 3.8-3.9, the main data required for the technical potential calculation are two: "$UEC_{(i, cur)}$" and "EEG_i". Of them, "$UEC_{(i, cur)}$" means knowing the energy consumption levels of various existing measures (or equipment), while "EEG_i" means knowing the energy efficiency levels of both existing measures and available advanced measures. The specific collection methods for them are introduced in Section 3.4.

3.3.2 Economic Potential

As shown before, economic potential refers to the aggregated energy-saving potential from all the selected advanced technical measures that are evaluated as being cost-effective. Therefore, the key for calculating economic potential becomes how to evaluate the cost-effectiveness of selected advanced measures.

In reality, there are often multiple options of efficiency-different advanced measures available for a certain energy end-use (for example, Tier 1-3 efficiency air conditioners for space cooling). Among these available measures, the ones with higher efficiency are usually more expensive. Therefore, the measure with the lowest-efficiency can be seen as people's baseline (or reference) option for the “replacements” and “additions” of household energy-use equipment stock, while the others could be seen as optimal options. Between the baseline option and each optimal option, two gasps exist: an energy efficiency gap and cost gap, as shown in Figure 3.6. The cost gap between the baseline measure and optimal measure is usually called incremental cost (EPA, 2007; ACEEE, 2009; Bourland, 2010).

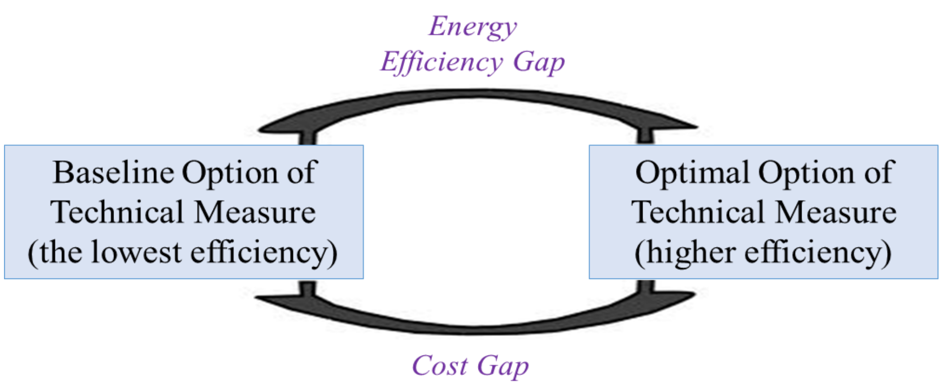

Figure 3.6 Gaps between Baseline and Advanced Technical Measures

(Source: Based on Walls, 2012)

According to the ACEEE (2009), the cost-effectiveness of a technical measure is determined by if its “*levelized cost of conserved energy” (LCOCE)* is less than the average retail energy price[44]. Based on that, from the government (society) perspective, the technical measures that can contribute to the “economic potential” of

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[44] “Levelized cost” means that the annual cost of the measure amortized over the life of the measure. The LCOCE is also referred to as LCCE in some research (NREL, 2012).

energy-savings can be screened by comparing their "*LCOCE*" with the actual cost of conserved energy. If the "*LCOCE*" of an advanced technical measure is no more than the actual cost of the saved energy, this measure is viewed as cost-effective (ACEEE, 2009). Accordingly, the aggregated energy savings from all the cost-effective measures represent the "economic potential." The judgment rule for cost-effectiveness can be presented as follows:

$$LCOCE\ (TM_i) \leq AC_{energy} \qquad (3.10)$$

where "TM_i" means an advanced technical measure "*i*"; "AC_{energy}" stands for the actual cost of relevant energy.

According to the NREL (2012), the "*LCOCE*" of a selected advanced energy-saving measure can be calculated as follows:

$$LCOCE(TM_i) = \frac{\boldsymbol{IC_{(i,0)}} + \sum_{t=1}^{n} \frac{\boldsymbol{OC_{(i,t)}}}{(1+d)^t}}{\sum_{t=1}^{n} \frac{\boldsymbol{CE_{(i,t)}}}{(1+d)^t}} \qquad (3.11)$$

where *"t"* stands for the lifetime of a certain advanced measure (accordingly *"t=1"* means *"the first year"* and *"t=n"* means *"the last year of its lifetime"*); "$IC_{(i,0)}$" stands for the incremental up-front cost of adopting the advanced measure *"i"*; "$OC_{(i,t)}$" stands for the caused incremental operation cost in the year *"t"* ; "$CE_{(i, t)}$" stands for the conserved energy in the year *"t"* caused by adopting the advanced measure *"i"*; *"d"* stands for the adopted discount rate.

It must be noted that in Equation 3.11, as shown in Figure 3.6, the incremental cost of advanced measures is calculated based on the cost of the baseline option.

The energy used in Chinese urban residential buildings is basically two types: electricity and natural gas (or liquefied petroleum gas instead), therefore, the "AC_{energy}" mainly means the actual cost of electricity or natural gas for urban China households.

In countries with a deregulated electricity (or natural gas) market, the actual cost of electricity (or natural gas) will be approximate to its retail price. However, this is not the case in the countries with a regulated utility market. Although China launched its utility (especially electricity) market deregulation reform in 2002, the Chinese utility markets are still largely regulated ones, and the retail price of electricity (or natural gas) is often intentionally underrated from its actual cost because of certain concerns (e.g., lower prices to facilitate economic growth, ignoring external cost of energy production and consumption, etc.)[45].

Therefore, in order to more accurately evaluate the "economic potential" of energy-savings in the countries with regulated utility markets like China, the actual cost of energy needs to be measured via three components – their retail price (*"RP"*), the government subsidy (*"GS"*) and their externality cost (*"EX"*), shown in Equation 3.12 as follows:

$$AC_{energy} = RP_{energy} + GS_{energy} + EX_{energy} \qquad (3.12)$$

where "AC_{energy}", "PR_{energy}", "GS_{energy}" and "EX_{energy}" respectively stand for the actual cost, retail price, received government subsidies, and externality cost of a

[45] This fact may not be surprising as "designing effectively functioning power markets proved to be an exceptionally complex task (Kurdgelashvili, 2008: 271)."

certain type of energy (e.g., electricity with the unit of "Yuan/kWh", natural gas with the unit of "Yuan/MJ").

Among the various "externalities" of energy use, negative environmental effects are often central to research concerns[46]. A comprehensive evaluation of the negative environmental effects of energy consumption is very challenging, and is obviously beyond the scope of this research. In this dissertation, the "externality cost" of energy use focus on carbon emissions cost. As several international or domestic carbon trading systems have been well established under the Kyoto Protocol worldwide (e.g., EU ETS since 2005), such externality cost can be conveniently estimated based on the monetary value of carbon emissions, shown in Equation 3.13 as follows:

$$EC_{energy} = MV_{emission.} \qquad (3.13)$$

where "$MV_{emission}$" stands for the monetary value of carbon emissions from consuming a unit amount of a certain type of energy.

Once all the cost-effective technical measures are identified based on the above a series of Equations 3.10-3.13, the "economic potential" of residential energy savings can be calculated based on Equations 3.7-3.9 through substituting cost-effective measures into the equations.

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[46] Environmental externalities refer to the uncompensated environmental effects of production and consumption that affect consumer utility and enterprise cost outside the market mechanism.

3.3.3 Achievable Potential

3.3.3.1 Analytical Framework for Achievable Potential

Different from the static analysis of technical or economic potential, analyzing achievable energy-saving potential (both maximum and possible) is a dynamic calculation process involving a certain time horizon. Therefore, projecting residential energy consumption (REC) naturally becomes the core basis for achievable energy-saving potential analysis (EPA, 2007).

Figure 3.7 shows the basic analytical framework for achievable energy-saving potential in this research.

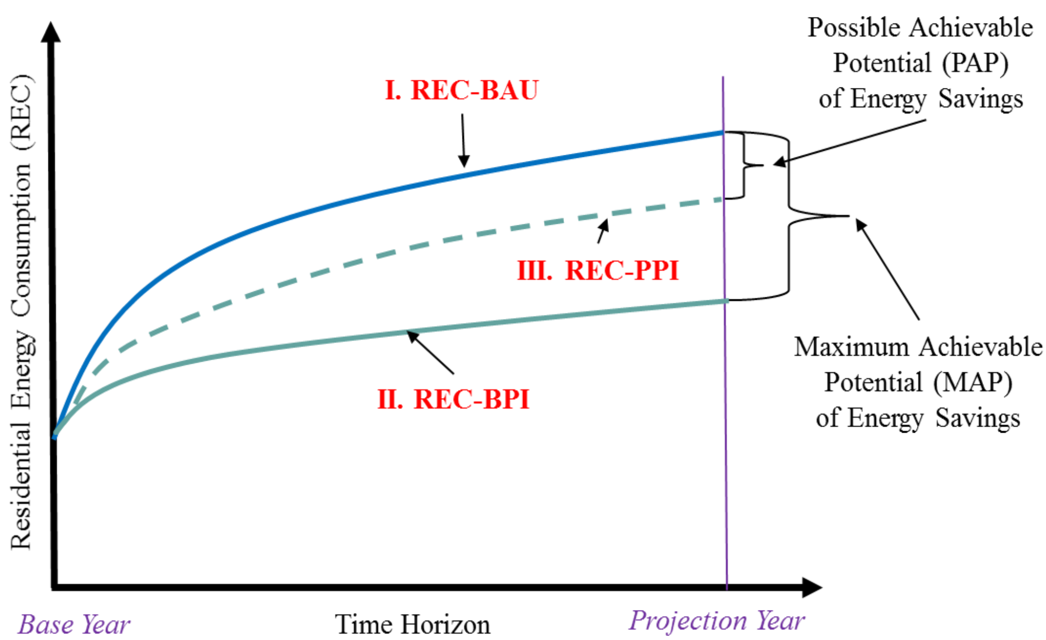

Figure 3.7 Analytical Framework for Achievable Energy-Saving Potential

(Source: Based on EPA, 2007)

In Figure 3.7, three REC projection curves are presented to structure the analytical framework for achievable energy-saving potential. They are: I) the projection under the "***Business-as-Usual***" scenario (REC-BAU); II) the projection under the "***Best-Policy-Intervention***" scenario (REC-BPI); and III) the projection under the "***Possible-Policy-Intervention***" scenario (REC-PPI).

Specifically, the REC-BAU scenario assumes that only the current available incentive policies and technical measures are applied in the projection period, and it takes into account both of the "gradual ramping-up" adoption process of advanced measures and individuals' adoption-decision making on them. The REC-BAU scenario is similar to Swisher et al. (1997: 45) "Dynamic Frozen Efficiency Scenario," which allows "replacement of retired equipment with new (more efficient) models on the market, but does not allow for introduction of new technologies which did not already exist in the marketplace in the base year." In the REC-BAU projection, all major socioeconomic factors related to REC are included (e.g., population, ownership of household appliances, household income, housing units, and housing floor space, etc.) (EIA, 2013). The REC-BAU functions as the baseline for achievable energy-saving potential analyses.

The projection of REC-BPI is based on the calculation approach for the REC-BAU. However, unlike the involvement of the factor of individuals' adoption-decision used in the REC-BAU projection, the REC-BPI scenario assumes that only those measures which have the highest energy efficiency will be adopted for the "Replacements and Additions" of equipment stock (EPA, 2007). This assumption represents the impact of best policy intervention scenario. Therefore, the gap between the REC-BAU and REC-BPI curves dynamically represents the full continuum of the MAP of residential energy savings within the selected time horizon.

The REC-PPI assumes different “to-be-tested” policy interventions (EPA, 2007). Under different policy interventions, the available advanced energy-saving measures (e.g., via tightening mandatory regulations) and individuals’ adoption-decision making on efficient appliances (e.g., via more favorable financial incentives) can be changed, resulting in different REC projections. Therefore, the gaps between the REC-BAU and different REC-PPI clearly show the continuum of PAP of energy savings. In this way, the PAP calculation can be used as a policy analysis tool to quantitatively evaluate the intervention effects of different incentive policies. It needs to be noted that the “to-be-tested” policies should be localized, appropriate and feasible: namely, their enforcement should not be beyond local capabilities (including institutional, human, and financial resources, etc.), and match local climate conditions and housing modes (EPA, 2007). It can be expected that the REC-PPI curve will shift to some extent between the REC-BAU and REC-BPI curves based on the underlying different policy intervention levels.

It needs to be noted that with involving the adoption of efficient measures, the “direct rebound effects” of energy use should be reflected into the projections of REC-BPI and REC-PPI.

In this research, the time horizon (or projection period) was decided to be ten years from the base year 2011. The main reason is that if a longer time horizon is used, technology advances may not be included accurately in the potential analysis.

3.3.3.2 EIA's National Energy Modeling System (NEMS)

As shown in Figure 3.7, the key for achievable potential analysis is to structure a projection model of residential energy consumption (REC). In this research, a bottom-up type REC projection model tailored for southern China cases is developed (see Section 3.3.3.3), mainly based on the "Residential Demand Module" of the EIA's (2013) "National Energy Modeling System (NEMS)."

The bottom-up modeling approach requires extensive data. Byrne et al. (2004: 163) stated that "a bottom-up analysis requires detailed information on current technology stocks in a country, the age distribution of equipment, and the energy and other characteristics of typical equipment routinely replacing items in the stock."

The EIA's NEMS is a computer-based (written in FORTRAN code) energy-economy modeling system. This model was first developed in 1993, and aims to "project the energy, economic, environmental, and security impacts on the United States of alternative energy policies and different assumptions about energy markets (EIA, 2009: 1)." The projection results from the NEMS model are presented in the EIA's publication of Annual Energy Outlook (AEO). There are thirteen modules in NEMS: four supply modules (oil and gas, natural gas transmission and distribution, coal market, and renewable fuels); two conversion modules (electricity market and petroleum market); four end-use demand modules (residential demand, commercial demand, industrial demand, and transportation demand); one module to simulate energy/economy interactions (macroeconomic activity); one module to simulate international energy markets (international energy); and one module that provides the mechanism to achieve a general market equilibrium among all the other modules (integrating module) (EIA, 2009).

In the NEMS, a “Residential Demand Module” (referred to as NEMS-RDM hereafter) is utilized to project the REC in the U.S. with a baseline year of 2005 and a projection horizon for as long as 25 years. In the NEMS-RDM, the REC projection is “determined as a function of the equipment and housing stock, average unit energy consumption (UEC), weighted equipment characteristics, and building shell integrity improvements (EIA, 2013: 11).” Running the NEMS-RDM requires extensive data that come primarily from the “Residential Energy Consumption Survey (RECS)” conducted by the EIA regularly (every four years) (EIA, 2014).

The NEMS-RDM is designed exclusively for the U.S. context, particularly in terms of covered energy end-uses, fuel types, building types (single-family homes, multifamily homes and mobile homes), and involvement of distributed energy generation, dynamical calculation for fuel prices (deregulated utility market), etc. Therefore, it cannot be directly applied to cases in China. Nevertheless, the NEMS-RDM still provides the general logic and fundamental calculation principles for structuring REC projections outside the U.S. In this research, based on the EIA’s NEMS-RDM, a REC projection model specifically tailored for southern China is developed (see the following Section 3.3.3.2).

There are two important sub-models in the NEMS-RDM, namely individuals’ “adoption-decision model” for advanced technical measures, and the turnover model of existing household energy use equipment stock (EIA, 2013). The type of individuals’ “adoption-decision model” has been introduced in Section 3.1.3.4 (see Equations 3.5 - 3.6). The equipment turnover model utilized in the NEMS-RDM is mainly established based on a survival rate function of equipment, which fits linearly into a Weibull-shaped decline (with $k<1$).

According to the EIA (2013), in reality any household energy use equipment stock in a year can be basically divided into three components: 1) the old stock (i.e., the pre-base year stock) which will continue to be used; 2) the old stock which needs to be replaced because of the retirement of equipment; and 3) the new added stock because of new constructions. As mentioned before, among the three components of equipment stock, only the last two components provide the potential opportunities for the adoption of energy efficient measures. The basic structure for the realistic turnover of equipment stock is shown in Figure 3.8.

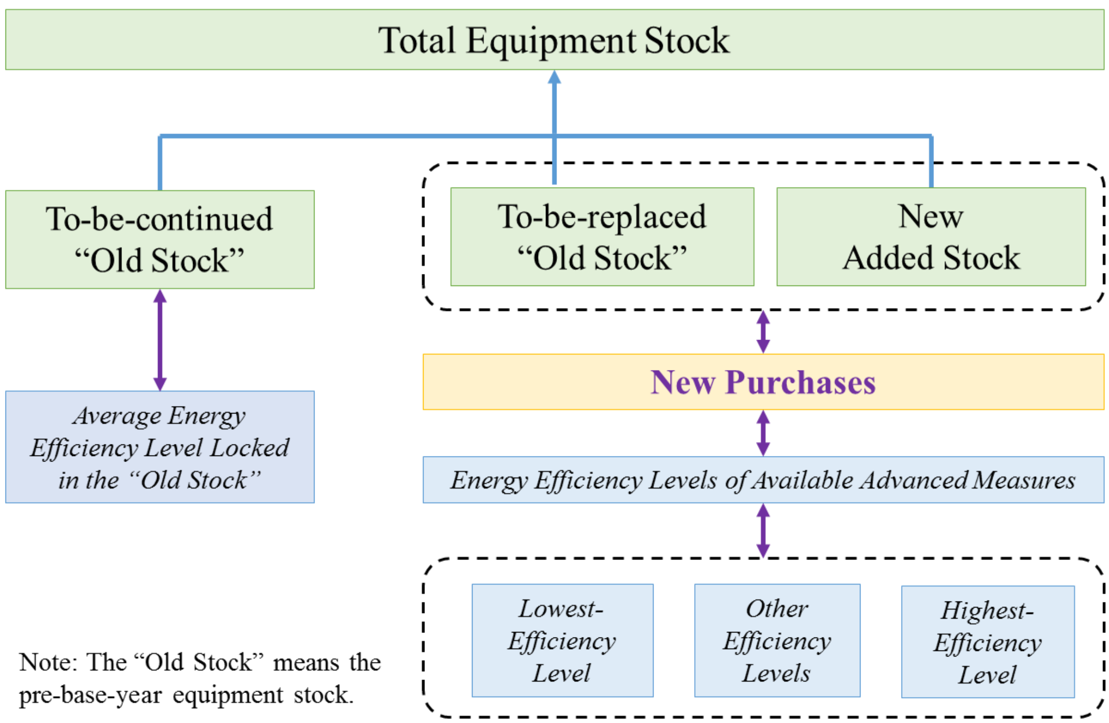

Figure 3.8 Gradual Ramping-Up Adoption Process of Advanced Technical Measures

(Sources: Based on EIA, 2013; EPA, 2007)

3.3.3.3 Maximum Achievable Potential

Based on the discussion in Section 3.3.3.1, it can be seen that the key for calculating "maximum achievable potential" of energy savings is to project the REC-BAU and REC-BPI. In this section, calculation methods for them applied to southern China are presented based on the basic logic and calculation principles utilized in the NEMS-RDM.

From Figure 3.8, it can be seen that there are generally two kinds of energy efficiency levels that are critical for achieving REC-BAU and REC-BPI: 1) the average energy efficiency (efficacy) level (EEL) locked into the old equipment stock (i.e., the pre-base-year stock) ("EEL_{old}"); and 2) the EEL of available advanced equipment in market for new purchases ("EEL_{new}"). Specifically, according to Chinese national EES&L schemes for appliances (i.e., Tier-1 to Tier-5 from high to low in energy efficiency), the "EEL_{new}" usually have several options, such as the highest ("EEL_{new_h}"), the lowest ("EEL_{new_l}") and those in between (i.e., "EEL_{new_m1}", "EEL_{new_m2}" and "EEL_{new_m3}" from high to low in efficiency)[47]. For annual new purchases of equipment, the available one with the lowest efficiency ("EEI_{new_l}") is the baseline option for consumers, meaning the reference option for assessing other available options. It needs to be noted that the EEL indicator varies for equipment. In China, the EEL of household appliances are stipulated in national EES&L schemes for appliances (see the details from Energy Label, 2014).

Among these different levels of energy efficiency, two things need to be noted: 1) the EEL of available advanced measures for a certain appliance may not be

[47] It needs be noted that for some appliances in China, their EES&L schemes are three-tiers. In these cases, there are only "EEI_{new_h}", "EEI_{new_m}" and "EEI_{new_l}".

consistent with the appliance's EES&L tiers. For example, according to the CLASP (2013), there are no Tier-3, 4 and 5 front-type clothes washers available for sale in the Chinese market although the EES&L scheme for it was designed to be five-tiers); and 2) the "EEI_{new_l}" may be equal to or much higher than the "EEI_{old}".

According to Kastovich-type adoption-decision model of advanced technical measures (i.e., Equations 3.5-3.6), the "simple payback time" of the equipment model with the highest efficiency (denoted as "$SPBT_{new\_h}$") can be calculated as follows:

$$EEG_{(i,new\_h)} = f\left(EEL_{(i,new\_h)}, EEL_{(i,new\_l)}\right) \qquad (3.14)$$

$$UEC_{(i,new\_l)} = UEC_{(i,cur)} \times [1 - f\left(EEL_{(i,new\_l)},\ EEL_{(i,old)}\right)] \qquad (3.15)$$

$$ESP_{(i,new\_h)} = UEC_{(i,new\_l)} \times EEG_{(i,new\_h)} \qquad (3.16)$$

$$IC_{(i,new\_h)} = FC_{(i,new\_h)} - FC_{(i,new\_l)} \qquad (3.17)$$

$$SPBT_{(i,new\_h)} = \frac{IC_{(i,new\_h)} - GI_{(i,new\_h,cur)}}{ESP_{(i,new\_h)} \times RP_{energy} + PBI_{(i,new\_h,cur)}} \qquad (3.18)$$

where the subscript "i" stands for a certain energy end-use equipment; "$EEG_{(i,\ new\_h)}$" stands for the energy efficiency improvement potential for the equipment "i" between the most efficient alternative "$EEI_{(i,\ new\_h)}$" and the baseline "$EEI_{(i,\ new\_l)}$" (expressed in the form of improved percentage from the baseline level)[48]; "$UEC_{(i,\ cur)}$" and

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48 It must be noted that the EEG calculation for different equipment varies, and closely relates to the involved EEL.

"$UEC_{(i, new\_l)}$" respectively means the average "Unit Energy Consumption (UEC)" of the pre-base-year stock and of the baseline option for the equipment *"i"*; *"ESP_i"* stands for the energy savings per unit equipment achieved from adopting the highest-efficiency option for the equipment *"i"*; "$IC_{(i, new\_h)}$" stands for the incremental cost of adopting the highest-efficiency equipment "*i*"; "$FC_{(i, new\_k)}$" and "$FC_{(i, new\_l)}$" respectively stand for the initial cost of the highest and lowest efficiency equipment "*i*"; "*GI*" and "*PBI*" respectively stand for the applied government financial incentives (i.e., tax incentives, subsidies, etc.) and annual performance-based incentives to the adoption of highest-efficiency equipment *"i"*; "RP_{energy}" denotes the retail price of relevant energy.

It must be noted that once the calculated "*SPBT*" is no more than zero (because of the significant scale of "*GI*"), the "*AR*" would be 1- meaning an adoption rate of 100%.

Similarly, through the above Equations 3.14-3.18 the "*SPBT*" for the other available options of energy efficient equipment (namely "*new_m1*", "*new_m2*", "*new_m3*") could also be calculated through substituting the related data of "*EEL*", "*FC*", "*GI*" and "*PBI*". Then, a comparison between the calculated "*SPBT*" of available options for a certain equipment *"i"* could be conducted as follows:

$$SPBT_{(i,new\_e)} = min\{SPBT_{(i,new\_h)},\ SPBT_{(i,new\_m1)},\ SPBT_{(i,new\_m2)}, SPBT_{(i,new\_m3)}\} \quad (3.19)$$

where the subscript "*e*" stands for consumers' preferred efficiency level among multiple options (i.e., "*h*", "*m1*", "*m2*" and "*m3*") for the equipment "*i*".

Therefore, there will be two "adoption rates" (i.e., "$AR_{(i,\, new\_e)}$" and "$AR_{(i,\, new\_l)}$") involved in the purchasing of new equipment, which could be calculated as follows:

$$AR_{(i,new\_e)} = e^{-0.3 \times SPBT_{(i,new\_e)}} \ (SPBT>0) \text{ or } AR_{(i,new\_e)} = 1 \ (SPBT \leq 0)$$

$$(3.20)$$

$$AR_{(i,new\_l)} = 1 - AR_{(i,new\_e)} \qquad (3.21)$$

Equation 3.19-3.21 actually represents the consumers' realistic choice among multiple available efficiency-different options based on Kastovich-type adoption-decision model, which assumes that the option with the shortest simple payback time is preferred and will be purchased by a certain percentage of potential consumers ("$AR_{(i,\, new\_e)}$"), and all the remaining potential consumers ("$AR_{(i,\, new\_l)}$") will chose the baseline option.

Once knowing the above adoption rates of available advanced options under the BAU scenario, the REC-BAU for a certain energy use equipment "i" in the year "j" could be calculated as follows:

$$Stock_{(i\_old,j)} = [1 - \beta_{(i\_old,j)}] \times Stock_{(i,0)} \qquad (3.22)$$

$$Stock_{(i\_new,j)} = Stock_{(i,j)} - Stock_{(i\_old,j)} \qquad (3.23)$$

$$\beta_{(i\_old,j)} = \frac{j}{m_i} \ (j \leq m_i) \ \ or \ \ \beta_{(i\_old,j)} = 1 \ (j > m_i) \qquad (3.24)$$

$$EEG_{(i,new\_k)} = f\left(EEI_{(i,new\_k)}, EEI_{(i,old)}\right) \quad (k{=}e,\ l) \qquad (3.25)$$

$$UEC_{(i\_new\_k,j)} = \left[\gamma_{(i,j)} \times UEC_{(i,cur)}\right] \times \left[1 - EEG_{(i\_new\_k)}\right] \quad (k{=}e,\ l) \quad (3.26)$$

$$REC_{(i,j)}^{BAU} = Stock_{(i\_old,j)} \times UEC_{(i,cur)} + AR_{(i,new\_e,j)} \times Stock_{(i\_new,j)} \times UEC_{(i,new\_e,j)} + AR_{(i,new\_l,j)} \times Stock_{(i\_new,j)} \times UEC_{(i,new\_l,j)} \qquad (3.27)$$

where "$Stock_{(i,0)}$" denotes the pre-base-year stock of a certain equipment "i"; "$Stock_{(i,j)}$" means the stock of equipment "i" in the year "j", which is achieved through the projection of housing stock and the ownership of equipment during the selected timeframe[49]; "$Stock_{(i\_old,\ j)}$" and "$Stock_{(i\_new,\ j)}$" respectively stand for the pre-base-year stock and new purchases of the equipment "i" in the year "j"; "$\beta_{(i\_old,j)}$" stand for the retirement coefficient for the pre-base-year stock of the equipment "i" in the year "j" (referring to the NEMS-RDM, it is assumed that the age of old equipment is evenly distributed within its lifetime if no further information available); "m_i" stands for the typical lifetime of the equipment "i"[50]; the "$UEC_{(i\_new\_e,\ j)}$" and "$UEC_{(i\_new\_l,\ j)}$" respectively stand for the "Unit Energy Consumption" of the available advanced option with the shortest "*SPBT*" and of the option with the lowest efficiency for the

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[49] For the Xiamen case study, this is presented in Sections 4.4.4.2 and 4.4.4.3 in Chapter 4.

[50] The typical lifetime of household appliances in China are stipulated in the national standard (SAC, 2012; AQSIQ and SAC, 2008).

equipment "i" in the year "j"; "$\gamma_{(i,j)}$" is a parameter to reflect the change of consumers' demand level of energy service for the equipment "i" along with their income increase in the year "j"[51]; "$REC_{(i,j)}^{BAU}$" stands for the REC-BAU of the equipment "i" in the year "j

Based on Equation 3.27, the REC-BPI (which assumes that all new purchases are the equipment with the highest efficiency) could be calculated as follows:

$$REC_{(i,j)}^{BPI} = Stock_{(i\_old,j)} \times UEC_{(i,cur)} + Stock_{(i\_new,j)} \times [UEC_{(i,new\_h,j)} + \varphi_{(i,j)} \times (UEC_{(i,new\_h,j)} - UEC_{(i,new\_l,j)})] \qquad (3.28)$$

where the "$REC_{(i,j)}^{BPI}$" stands for the REC of the equipment "i" in the year "j" under the scenario of *Best-Policy-Intervention*; "$\varphi_{(i,j)}$" stands for the coefficient of "direct rebound effects" for the equipment "i" in the year "j" (defined in Equation 3.1).

With the calculated "$REC_{(i,j)}^{BAU}$" and "$REC_{(i,j)}^{BPI}$", the "maximum achievable potential" of energy savings (in the form of a reduction percentage from the REC-BAU) could be estimate as follows:

$$ESP_j^{MAP} = 1 - \sum_i REC_{(i,j)}^{BPI} / \sum_i REC_{(i,j)}^{BAU} \qquad (3.29)$$

where "ESP_j^{MAP}" stands for the "maximum achievable potential (MAP)" of energy savings in the year of "j".

[51] For the Xiamen case study, this is presented in Section 4.4.4.4 in Chapter 4.

3.3.3.4 Possible Achievable Potential

The presented calculation Equations 3.14-3.27 reveal that promoting energy-saving incentive policies (e.g., mandatory, financial, etc.) can exert influences on available advanced technical measures as well as individuals' adoption rates for them, and consequently result in different scales of achievable residential energy savings. Therefore, the series of Equations 3.14-3.27 could be used as a policy analysis tool to evaluate the real-world impact of various policy interventions on REC - namely realizing the analysis of "possible achievable potential (PAP)." Accordingly, the key for the PAP analysis lies in structuring localized, appropriate and feasible "to-be tested policy" intervention cases.

3.3.3.5 Policy Cases for Achievable Potential Analyses in Xiamen

As presented in Section 3.3.3.1, two kinds of policy cases need to be identified or structured. The first kind looks at the current incentive policies, which are used for the REC-BAU projection. The second kind is to structure the "to-be-tested" policy intervention cases, which are used for the estimation of REC-PPI. These "to-be-tested" policy intervention cases should be appropriate and feasible to the local context (e.g., climate, housing and energy use patterns, governments' enforcement capacity, etc.). The review and assessment of current energy-saving incentive policies in China (see Chapter 2) found a sound basis for structuring these two kinds of policy cases for the Xiamen case study.

Figure 3.9 summarizes the BAU mandatory policies (i.e., building energy code and EES&L schemes for appliances) that are applied to Xiamen's residential buildings[52]. Besides these mandatory policies, the subsidy program for efficient appliances implemented during 2012-2013 (see details in Section 3.3.2.1) should also be taken into account in the calculation of REC-BAU, as it lies in the projection time horizon of 2011-2020 in this research.

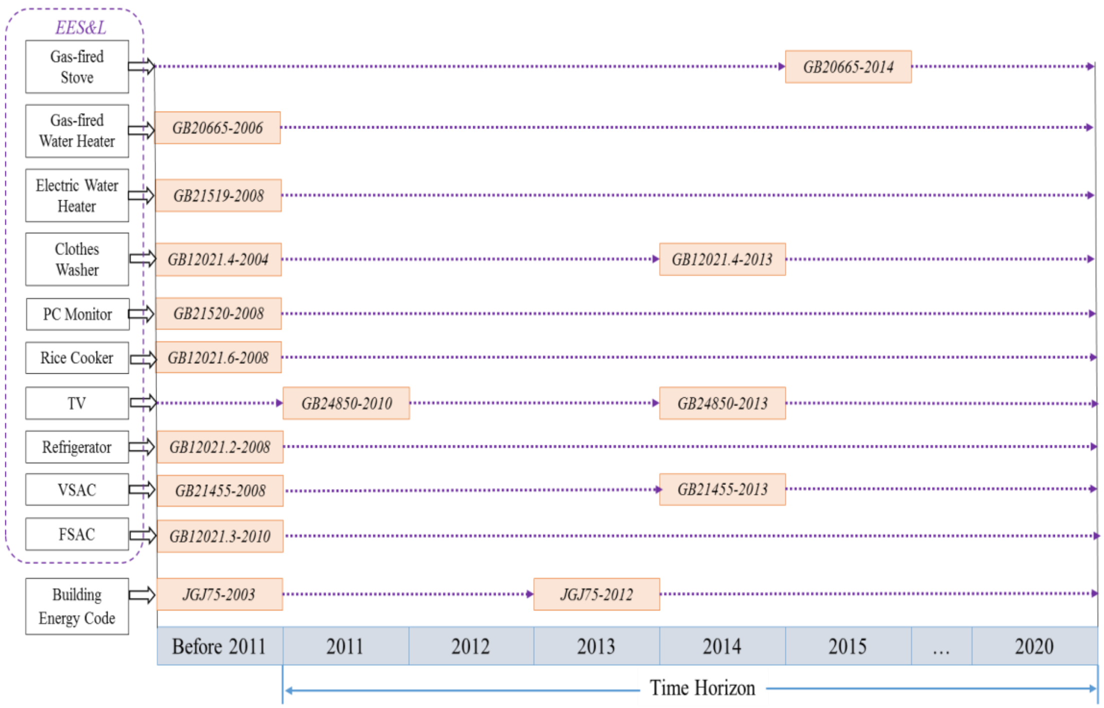

Figure 3.9 Existing Mandatory Policies for Saving Residential Energy Use in Xiamen

(Sources: Based on MOHURD. 2012b; Energy Label, 2014)

52 The enforcement dates for some mandatory policy instruments are adjusted to the whole year for the convenience of REC-BAU calculation. Actually, the enforcement date for GB12021.4-2013, GB24850-2013 and GB21455-2013 is October 1, 2013; for the GB24850-2010 it is December 1, 2010; for the JGJ75-2012 it is April 1, 2013; for the GB20665-2014 it is April 1, 2015.

Based on the policy review and assessment in Chapter 2, there are four types of policy instruments appropriate for and able to exert a significant impact on residential energy savings in the city of Xiamen. They are summarized in Table 3.2.

Table 3.2 Current Feasible Incentive Policies for Residential Energy Savings in Xiamen

Policy Incentives	Influencing Mechanisms on Energy Savings
Building Energy Code	Determining the energy performance of new buildings by mandatory approach
EES&L Schemes for Appliances	Determining the available options of energy efficient appliances by mandatory approach
Pricing of Electricity and Natural Gas	Determining the adoption rates of available options of energy efficient appliances
Subsidies to Efficient Appliances	Determining the adoption rates of available options of energy efficient appliances

(Source: Based on the author's policy review)

Among the four types of feasible policy incentives, the "building energy code" and "EES&L scheme for appliances" are mandatory, which could finally determine the "*UEC*" of the available options of energy efficient appliances. In comparison, the two financial instruments of "energy pricing" and "subsidizing" function to influence consumers' adoption decisions of advanced technical measures.

The "to-be-tested" policy cases structured for the Xiamen case study should be based closely on the four types of policy incentives listed in Table 3.2. They are introduced respectively below.

The building energy code (i.e., JGJ75-2012) currently applied in Xiamen has been enforced since 2013 (MOHURD, 2012). Given the long code revision cycle in China (typically about 10 years or more) (Kang, 2008), a new version of code may not be issued before 2020. Nevertheless, in order to test the intervention effects of building energy code in Xiamen, this research assumes a code revision in 2018 (representing a more appropriate revision cycle of 5 years). In China, the first and second code revisions are usually respectively about 30% and 50% lower from the baseline energy consumption (Tu, 2010; Kang, 2008). According to Cai (2006), the JGJ75-2012 is about 40% less in cooling load from its previous 2003 version, therefore, it is estimated that the next JGJ75 code revision for Xiamen will require a further reduction of about 15% in cooling load from the current JGJ75-2012.

In the *Development Plan of Chinese Household Appliances during the 12th Five-Year-Plan (2015-2020)* (CHEAA, 2011), it was suggested that the energy efficiency of main household appliances in China should be improved by about 15% every five years. Accordingly, it is assumed in this research that the EES&L schemes for three key energy-intensive appliances (i.e., ACs, TVs, and refrigerators) will be revised by requiring a 15% additional efficiency improvement in 2018, considering the fact that the usual revision cycle of EES&L schemes is about 5-9 years in China (Energy Label, 2014). These three types of appliances together account for almost half of the electricity consumption in Xiamen's households.

As mentioned in Chapter 2, a subsidy program for efficient appliances (covering ACs, refrigerators, etc.) had been implemented in China during 2012-2013. In that program, the subsidy levels (measured in the form of percentage of appliances' retail price) were set to be about 10% on average (CLASP, 2013). However, such subsidy levels in the EU member countries are usually set at about 20-30% to be effective (TOP10, 2012). For that reason, three levels of subsidy for efficient appliances were assumed in this research as the "to-be-tested" policy cases, namely a low-level case (10%), a modest-level case (20%), and a high-level case (30%).

Given China's context, the "actual cost" of household energy (mainly electricity and natural gas in urban China) should comprise three components: regulated retail prices ("RP"), government subsides ("GS") and their environmental externality costs ("EX"). Consequently, the three "to-be-tested" policy cases of energy pricing are assumed in this research for the PAP analysis in Xiamen's residential buildings were as follows: 1) pricing based on RP+GS; 2) pricing based on RP+EX; and 3) pricing based on RP+GS+EX. As for the "EX", in this research, only the carbon emissions cost of energy use is taken into account because the trading systems for other types of pollutants (like SOx and NOx) have not been implemented in China yet.

3.4 Required Data and Collection Methods

According to the above proposed analytical approaches for the four types of energy-saving potential (i.e., Equations 3.7-3.29) for southern China, the required data and related data collection methods for this study are summarized in Table 3.3.

Table 3.3 Required Data and Collection Methods

No.	Date Categories	Collection Methods
1	Base-year energy consumption levels (i.e., UEC) of household energy use equipment	Household Energy Use Survey
2	Base-year energy efficiency levels of household energy use equipment	
3	Energy efficiency levels of available advanced household energy use equipment	Market Survey
4	Incremental cost of available advanced household energy use equipment	
5	Time horizon of projection	Ten years
6	Typical lifetime of household energy use measures	Literature Review
7	Appropriate discount rate	
8	Retail prices of related energy	
9	Subsidies to related energy	
10	Carbon emissions cost of related energy	
11	Coefficients of direct rebound effects of various household energy use	
12	Projection of housing stock and household equipment stock within the selected time horizon	
13	Projection of people’s demand level of household energy services within the selected time horizon	
14	Current energy-saving incentive policies for residential buildings	Policy Review
15	Appropriate “to-be-tested” incentive policy intervention cases	

(Source: Summarized based on Equations 3.7-3.28)

It can be seen that there are in total fifteen categories of data required for the analysis of residential energy-saving potential in southern China. These data can be generally obtained through four collection methods: 1) household energy use survey; 2) market survey; 3) literature review; and 4) policy review.

Among the fifteen categories of data, the D1 is fundamental for potential analysis. In general, the D1 can be obtained by three methods, namely existing databases, field testing and household energy use surveys. The existing database is the most convenient way. A good example is the “Residential Energy Consumption Survey (RECS)” in the U.S., which is conducted by the EIA every four years through a large-scale sample survey nationwide. The RECS is also the primary source of data inputs for the EIA’s NEMS-RDM (EIA, 2013). Unfortunately, neither a credible nor comprehensive database exists in China at present (Lin and Liu, 2015). Of the other two feasible options (i.e., field testing and household energy use surveys), the method of “field testing” is very costly and time-consuming as much testing equipment (smarter meters, etc.) needs to be installed in diversified residential energy end-uses in enough households. In practice, this method is used only for research involving small samples, and is unaffordable for a large-scale collection of representative D1 data.

In this dissertation, the method of “household energy use surveys” is used to collect the D1 data for the Xiamen case study, by referencing the questionnaire of EIA’s RECS. In the survey, four kinds of data are collected: 1) basic features of households (floor space, buildings age, buildings type, number of occupants, etc.); 2) annual household energy consumption through recording their energy bills; 3) deployment of household energy use equipment (ownership, models, capacity, energy efficiency tiers, nameplate wattage, etc.); and 4) use patterns of household equipment (use schedule, time, frequency, etc.). The D1 data could be reliably collected based on the survey questionnaire through certain analysis, calculation, as well as necessary assumptions. The details about the Xiamen Household Energy Use Survey will be introduced in Section 4.1 of Chapter 4. It can be seen that the D2 data can be directly collected from the designed household survey.

The data categories of D3 and D4 are collected mainly through a market survey. In the market survey, basic types, energy efficiency levels and retail prices of household energy use equipment in the Chinese market are surveyed. In this dissertation, such data are collected primarily through the official SUNING website (SUNING is one of the largest online dealers in China). The details about the market survey for the Xiamen case study will be introduced in Section 4.2 of Chapter 4.

For this research, D5 (i.e., time horizon) is decided to be ten years, considering the fact that a longer time may not well incorporate technology advances into the energy savings potential analysis.

In general, the categories of D6-D13 can be collected through relevant literature reviews (specific analyses or estimates are needed for obtaining D10, D12 and D13). The details about these literature reviews will be presented in Sections 4.4.2, 4.4.3 and 4.4.4 of Chapter 4.

The data categories of D14 and D15 can be primarily identified (or structured) through a critical review of China's current energy-saving incentive policies targeting buildings, which was presented in Chapter 2. The details about D14 and D15 for the Xiamen case study have been presented in Section 3.3.3.5 of this chapter.

3.5 Chapter Summary

This chapter introduced the proposed methodology for residential energy-saving potential analysis in southern China, including conceptual frameworks, analytical approaches and data collection methods, etc.

First, based on the literature review, two basic intervention strategies for achieving energy savings in the residential buildings sector were identified. These are "technological progress" and "change of people's energy use behaviors." A further discussion revealed that the two strategies might be closely linked via two key concepts: rebound effects of energy efficiency improvements and individuals' adoption-decision making of advanced technical measures. A detailed literature review and discussion on the "rebound effects" in residential buildings was given. Based on the review, the "direct rebound effects" of energy savings related to the adoption of energy efficient measures was suggested for incorporation into the energy-saving potential analysis. In addition, through reviewing the research findings on people's adoption-decision making from diverse disciplinary perspectives (including social psychology, behavioral economics and technology diffusion theories), a widely-used Kastovich-type adoption-decision model of advanced technical measures was introduced for the energy-saving potential analysis in this research.

Then, mainly by referring to the U.S. EPA's (2007) *Guide for Conducting Energy Efficiency Potential Studies*, a modified overall conceptual framework of energy-saving potential analysis was proposed, which includes four types of potential analysis, namely technical potential, economic potential, maximum achievable potential and possible achievable potential. The first two types of potential analysis assume "complete" and "immediate" replacement of existing technical measures by advanced ones, and are, therefore, a kind of static measurement of energy-saving potential. In comparison, the achievable potential analyses are based on dynamic potential calculations focusing on: 1) gradual ramping-up adoption process of advanced energy efficiency measures; and 2) individuals' adoption-decision making on these measures. Of the two types of achievable potential analysis, the "maximum achievable potential" assumes the complete adoption of the most efficient measures in the realistic gradual ramping-up adoption process; therefore it implies the theoretical maximum energy savings which are realistically feasible within a certain time horizon. On the other hand, the possible achievable potential analysis depends closely on certain incentive policy cases, and therefore provides a quantitative way to evaluate the realistic impact of optional incentive policies on residential energy savings. Different types of potential analysis serve different research needs. The static potential analysis could guide policymakers in evaluating the general policies for certain sectors, while the achievable potential analyses could help them design specific incentive policies within a certain sector.

Next, based on a broad literature review, the specific analytical approaches to the four types of potential analysis were respectively proposed. Especially, in order to implement the achievable potential analyses in the case study city, a residential energy consumption (REC) projection model specifically tailed for southern China was developed, mainly based on EIA's (2013) NEMS-RMD. This established REC projection model could be used as a policy analysis tool to quantitatively evaluate the real-world impact of various incentive policies on residential energy savings. The overall structure of this REC projection model is shown in Figure 3.10.

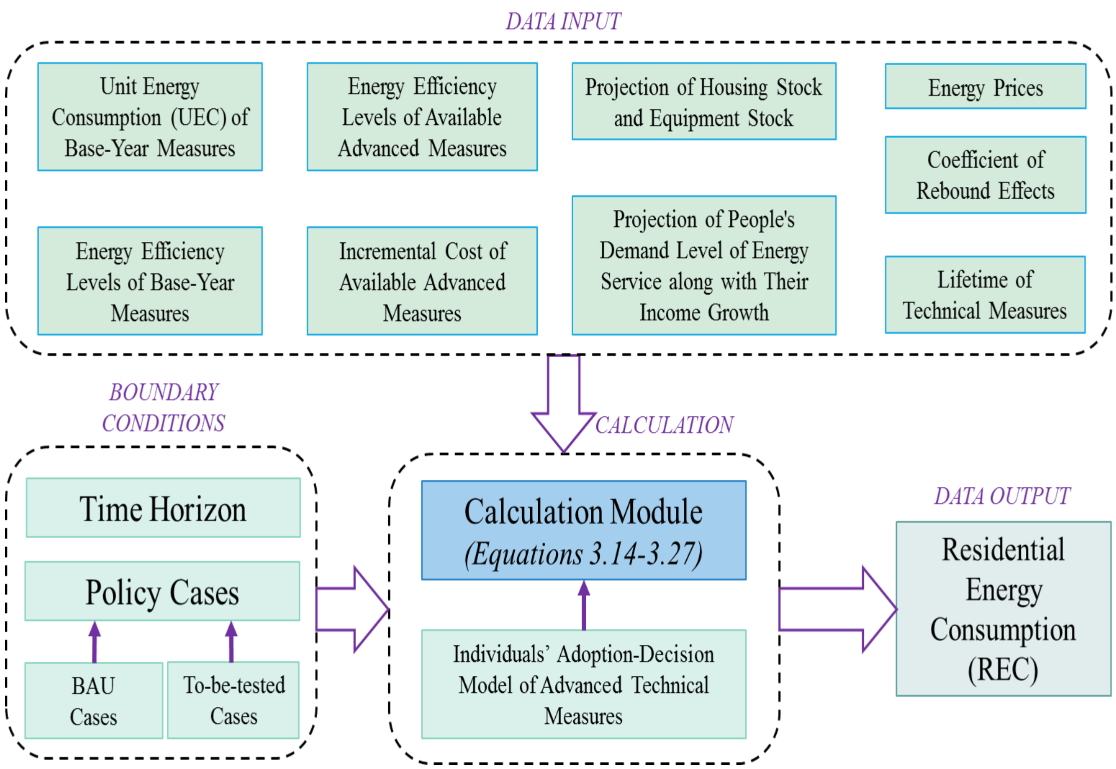

Figure 3.10 Structure of the REC Projection Model Developed in this Research

(Source: Based on EIA, 2013)

This REC projection model comprises four modules: a data input module, a boundary conditions module, a calculation module, and a calculation results output module. The core for the calculation module lies in the Kastovich-type adoption-decision model (expressed in Equations 3.5-3.6). The module of boundary conditions includes two kinds: time horizon and policy cases. For any projection, these two kinds of boundary conditions need to be identified first. Within a certain time horizon, the REC projection in a selected city depends completely on the involved policy intervention cases. For the analysis of "possible achievable potential," the "to-be-tested" policy cases must be involved. These "to-be-tested" policy cases should be appropriate and feasible for the selected city, and primarily be structured from a detailed review and assessment of current incentive policies. This REC projection model could largely facilitate the design of effective energy-saving incentive policies for buildings in southern China.

Finally, as extensive data are required for the potential analysis, their collection is important to the research. The collection methods for the required data were summarized in Table 3.3. Besides deciding an appropriate study time horizon that fits the research purpose, there are mainly four data collection methods needed in this research: 1) the "Household Energy Use Survey" (similar to the EIA's RECS) for comprehensively understanding the patterns of local residential energy consumption; 2) the "Market Survey" for understating the characteristics of advanced technical measures available in the local market; 3) the broad "Literature Review" for obtaining certain calculation parameters and making key assumptions; and 4) the "Policy Review" for identifying BAU policy cases and structuring feasible "to-be-tested" policy cases for achievable potential analyses.

Chapter 4

DATA COLLECTION FOR RESIDENTIAL ENERGY-SAVING POTENTIAL ANALYSIS IN XIAMEN

The methodology for the energy-saving potential analysis in southern Chinese urban residential buildings was presented in Chapter 3. Extensive data are required for such an analysis. In this Chapter, data collection for the Xiamen case study is introduced.

Five sections are included in this Chapter. Section 1 introduces a household energy use survey in Xiamen. The survey provides first-hand data on the City's residential energy use patterns. Based on an analysis of the survey results, Section 2 lists appropriate and feasible technical measures for achieving residential energy savings in the city of Xiamen. Section 3 presents the energy efficiency improvement potential of various household appliances, as well as related incremental cost through a market survey. In Section 4, the additional data required for the potential analysis in Xiamen are presented, including calculation parameters (e.g., appropriate discount rate, actual cost of fuels, etc.), and the projection of important socioeconomic factors related to household energy use (population, housing stock, household energy use equipment stock, people's demand level of energy service, etc.). These data are obtained mainly through a review of related literature as well as estimates based on specific calculations. A brief chapter summary is included in Section 5.

4.1 Household Energy Use Survey in Xiamen

4.1.1 Survey Methodology

4.1.1.1 Data Collection Methods

The survey questionnaire (shown in Appendix A) was designed by referring to the questionnaires used by the EIA for its RECS (Residential Energy Consumption Survey). The survey targeted four groups of data: 1) total household energy consumption for an entire year; 2) the deployment (ownership, type, model size, energy efficiency levels, nameplate wattage, etc.) of various household appliances; 3) the use patterns of the appliances (use schedule, time, frequency, etc.); 4) the information related to certain household features (housing floor space, building's age, buildings type, number of occupants, education level of occupants, and household income, etc.). The survey was implemented through a face-to-face questionnaire interview by pre-trained interviewers[53].

The required survey data and information were obtained entirely through the interviewers' on-site audit and careful consultation with the occupants. Specifically, the data of total household energy consumption were obtained by checking the household's energy bills or the transaction records of their utility "smart cards" (a kind of chip card by which residents can buy a lump sum of electricity or natural gas in advance for later use). For the deployment of household appliances, the interviewers were required to check the nameplates of various appliances. The use patterns of

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[53] This household energy use survey was completed by pre-trained graduate students from Xiamen University who have extensive experience in conducting research surveys.

appliances and the information of household features were obtained through careful communication with occupants[54].

To map the energy use patterns in Xiamen's households, a general "flow chart" of household energy use was first structured based on the THUBERC's (2013) study method of residential energy consumption in urban China, shown in Figure 4.1[55]. The household energy use in Xiamen can be divided into five basic end-use groups: namely, cooking (by gas-fired cook stoves), lighting, plug-in appliances (refrigerators, TVs, rice cookers, etc.), water heating, and space cooling, which are served generally by four types of energy: electricity, natural gas[56], heat, and renewable energy.

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[54] The survey was conducted during weekends to ensure meeting with the principal members of households (i.e., main income-earners).

[55] THUBERC's (2013) classification method also includes the end-use of space heating. However, space heating is not applied to the Xiamen case because of the local climate.

[56] The survey also involved a few households using liquefied petroleum gas (LPG); however, none of them are included in the final data analysis because of the lack of some key data (e.g., housing floor space) in these households.

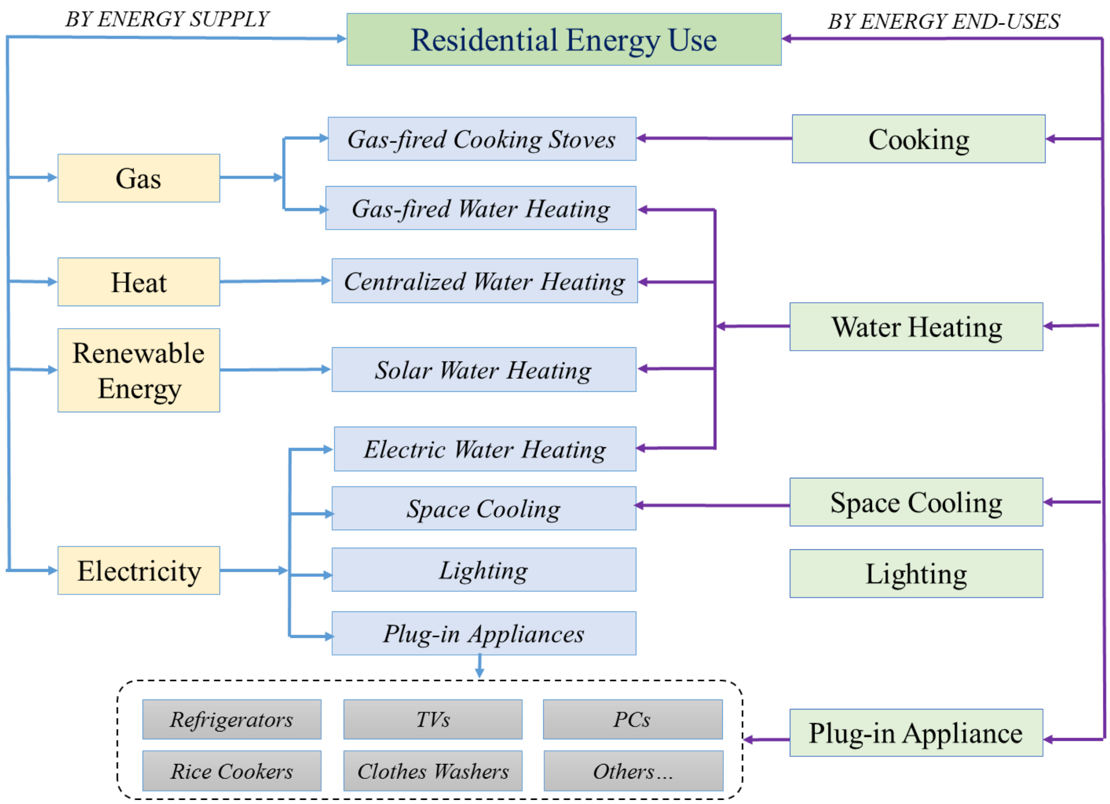

Figure 4.1 Household Energy Consumption Structure in Urban Xiamen

(Source: Based on THUBERC, 2013)

It is important to note that the energy consumption discussed in this research focuses exclusively on final (on-site) energy use, but not primary energy use. Where energy consumption of different types of energy need to be aggregated (e.g., total household energy consumption), a consolidated unit of "megajoule (MJ)" is used. The energy conversion parameters for the Xiamen case are shown in Table 4.1.

Table 4.1 Energy Conversion Parameters in Xiamen

Type of Final Energy	Unit	Conversion
Electricity	1 kWh	1kWh = 3.6 MJ
Natural Gas	1 m^3	1 m^3 = 38.17 MJ[1]

Note: [1] The average low calorific value of natural gas in Xiamen.

(Source: GFP, 2011)

4.1.1.2 Data Analysis Methods

As shown in Figure 4.1, the overall energy consumption intensity (measured in units of $MJ/m^2 \cdot year$) in each of Xiamen's households can be expressed through the following equation:

$$THEC = EC_{cooking} + EC_{lighting} + EC_{wh} + EC_{appliance} + EC_{sc} \qquad (4.1)$$

where "*THEC*" stands for the total household energy consumption; "$EC_{cooking}$", "$EC_{lighting}$", "EC_{wh}", "$EC_{appliance}$" and "EC_{sc}" respectively stand for the energy consumption for cooking, lighting, water heating, plug-in appliances and space cooling in Xiamen's households.

Among the above six variables, the "*THEC*" can be collected directly through checking the utility bills or utility cards' purchasing records of the interviewed households. The calculation of energy consumption intensity for each household energy end-use group (i.e., cooking, lighting, plug-in appliances, water heating and space cooling) is based mainly on the research of Swisher et al. (1997) and the EIA (2013).

As all the surveyed Xiamen households use natural gas for cooking, the energy consumption intensity for cooking in Xiamen can, therefore, be calculated from the households that do not use gas-fired water heaters. It needs to be noted that the energy use term for "cooking" in this research means only the energy consumed through gas-fired stoves, while the other cooking appliances (rice cookers, microwave ovens, etc.) are grouped into the end-use of plug-in appliances.

Based on Swisher et al. (1997) estimation method for household lighting energy use, the energy use for lighting per household can be estimated as follows:

$$EC_{lighting} = \sum A_i \times IW_i \times UT_i \times 365/1000 \qquad (4.2)$$

where "$EC_{lighting}$" is the average energy consumption for lighting (in units of kWh/ household·year); the subscript "i" stands for the room type (e.g., living-room, bedroom, study room, dining-room, kitchen, bathroom); "A_i" stands for room coefficient, meaning the numbers of a certain type of room per household on average in Xiamen; "IW_i" (in units of watt) and "UT_i" (in units of hours/day) respectively mean the average installed wattage and use time of lighting lamps in a certain type of room.

In Chinese residential buildings, hot water is used mainly for showering, and not often used for other purpose (e.g., bathing, dish washing, clothes washing, room cleaning) (THUBERC, 2013). Accordingly, the energy consumption for water heating in Xiamen households can be estimated based on people's energy demand for showering. The calculation method is shown as follows:

$$EC_{wh} = [Q \times N \times F \times C \times (t_{out}-t_{in}) \times 365/7]/\eta \qquad (4.3)$$

where "EC_{wh}" is the average household energy consumption for water heating (in units of kJ/household·year); "Q" is the average water amount used for a shower per time per person (in units of liter/person·time); "N" is the average household size (namely the average numbers of household members); "F" is the surveyed average shower frequency (in units of times/person·week); "C" is the specific heat capacity of water (namely 4.186 kJ/liter·°C); "t_{in}" and "t_{out}" are the temperature of inflow and outflow water (in units of ℃) respectively (the "t_{in}" is usually determined by the temperature of local supplied water, while "t_{out}" is usually within the range from 38°C to 43°C)[57]; "η" stands for the energy efficiency of water heaters (for electric heaters, solar heaters and centralized water heating, the "η" can be viewed as 100%).

As mentioned in Chapter 3, in the NEMS-RDM (EIA, 2013), the electricity consumption of plug-in appliances (i.e., "$EC_{appliance}$") in residential buildings is obtained by multiplying two parameters of appliances together, namely the ownership rate and Unit Energy Consumption (UEC - typically in units of kWh/year). The survey collects the data related to the deployment and use patterns of various household appliances. Based on these data, the UEC of the appliances could be estimated through multiplying their usage time and actual wattage.

However, there is a significant challenge related to such UEC estimation. For some appliances (e.g., irons, rice cookers, microwave ovens), their actual wattage is equal (or almost equal) to their nameplate wattage collected in the survey, while for certain appliances the two wattages (i.e., actual and nameplate) are often found to be

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[57] An intermediate temperature 40 ℃ for "t_{out}" is used in this research.

unequal[58] (e.g., TVs, PCs). Therefore, selecting appropriate actual wattage for certain appliances is important for reliable calculation of the UEC. To deal with this challenge, in this research obtaining the average actual wattage of certain appliances is done in two ways: 1) research on modeling actual wattage of several household appliances (Ren and Hu, 2012); 2) a number of testing reports on appliances' real electricity consumption on certain Chinese websites[59].

The UEC method is, unfortunately, not very suitable for estimating the electricity consumption of air conditioners in Chinese households. Chinese households usually do not have centralized air conditioning systems which are popular in U.S. residential buildings. Almost all Chinese households adopt non-centralized systems by installing split-type air conditioners (AC) in their rooms. In addition, the operation modes of air conditioning systems in the two countries are quite different. In the U.S. the system is usually operated for 24 hours a day and throughout the whole house, while this is not the case in China (THUBERC, 2013). The AC use mode in Chinese households varies significantly. For example, the author's Xiamen survey shows that some households prefer to turn on only one AC unit and make all occupants stay in that room, while others will not turn on the AC units in different rooms at the same time when needed. Therefore, the AC use time is difficult for households to be reliably reported. In this sense, it is much better to treat all the AC units in a household as a

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[58] Such a difference is caused mainly by the required operation mode for the measurement of some appliance's nameplate wattage, which is not consistent with the usual use mode of that appliance by general consumers.

[59] There are some websites focusing on studying the energy performance of household appliances in China, including http://www.pconline.com.cn; http://www.ea3w.com/; http://www.zol.com.cn/, etc.

whole system rather than individual units. With the above thoughts in mind, the energy consumption intensity for space cooling (i.e., "EC_{sc}") in this research is obtained through a related literature review.

Lastly, it is important to note that the sum of the energy consumption intensities for cooking, lighting, water heating, plug-in appliances and space cooling may be less than the surveyed "*THEC*." This gap can be explained by the disaggregated nature of the plug-in appliances. Ownership of plug-in appliances varies among households, and some of them are easily missed during the survey, particularly those that do not enjoy popular ownership, or not often used. Nonetheless, the gap should not be significant, as these missed plug-in appliances do not consume much electricity due to their very low ownership, short use time and often small actual wattage.

In summary, given the fact that it is very costly (or unaffordable in the case of this research) to implement field testing of energy consumption in the residential buildings sector, the above-introduced household energy use survey was then used as the alternative data collection method. Although the data obtained from household survey may not perfectly portray the energy use patterns in residential buildings versus field testing, it could still provide researchers with a reasonable estimate of such patterns, particularly for policy-focused studies.

Moreover, in order to further examine the credibility of obtained data from the household energy use survey, a critical parameter of "electricity consumption intensity (ECI)" was used to check the results. Usually, the "*ECI*" (in units of $kWh/m^2 \cdot year$) in a Chinese city could be calculated based on three macro statistical data which are shown in the city's Statistical Yearbook, namely a city's total population, a city's total residential electricity consumption, and average housing floor space per capita. On the other hand, the "*ECI*" can also be obtained from the survey by aggregating the electricity use intensities of various end-uses (including space cooling, lighting, plug-in appliances and electric water heating). It can be seen that the two "*ECI*" are obtained from two completely different methods – macro-based statistics and a micro-based survey. Therefore, if the gap between the two "*ECI*" is small, it means that the data collected from the household survey are quite reliable.

4.1.2 Survey Analysis

4.1.2.1 Analysis of Survey Samples

Surveys were conducted in 150 randomly-selected households in Xiamen. These households were geographically dispersed in thirty five sub-districts within the city's four core municipal districts[60] (i.e., Hu Li, Si Ming, Ji Mei and Tong An). As there are total 315 sub-districts in Xiamen (XBS, 2012a), the survey covered over one-tenth of them. Such a wide distribution of households in the city effectively ensured the representativeness of the survey samples, which can be observed from the distribution of some key features of the surveyed households (namely housing floor space, buildings age, household size, age of occupants, household income, and education level of occupants), as shown in Figure 4.2.

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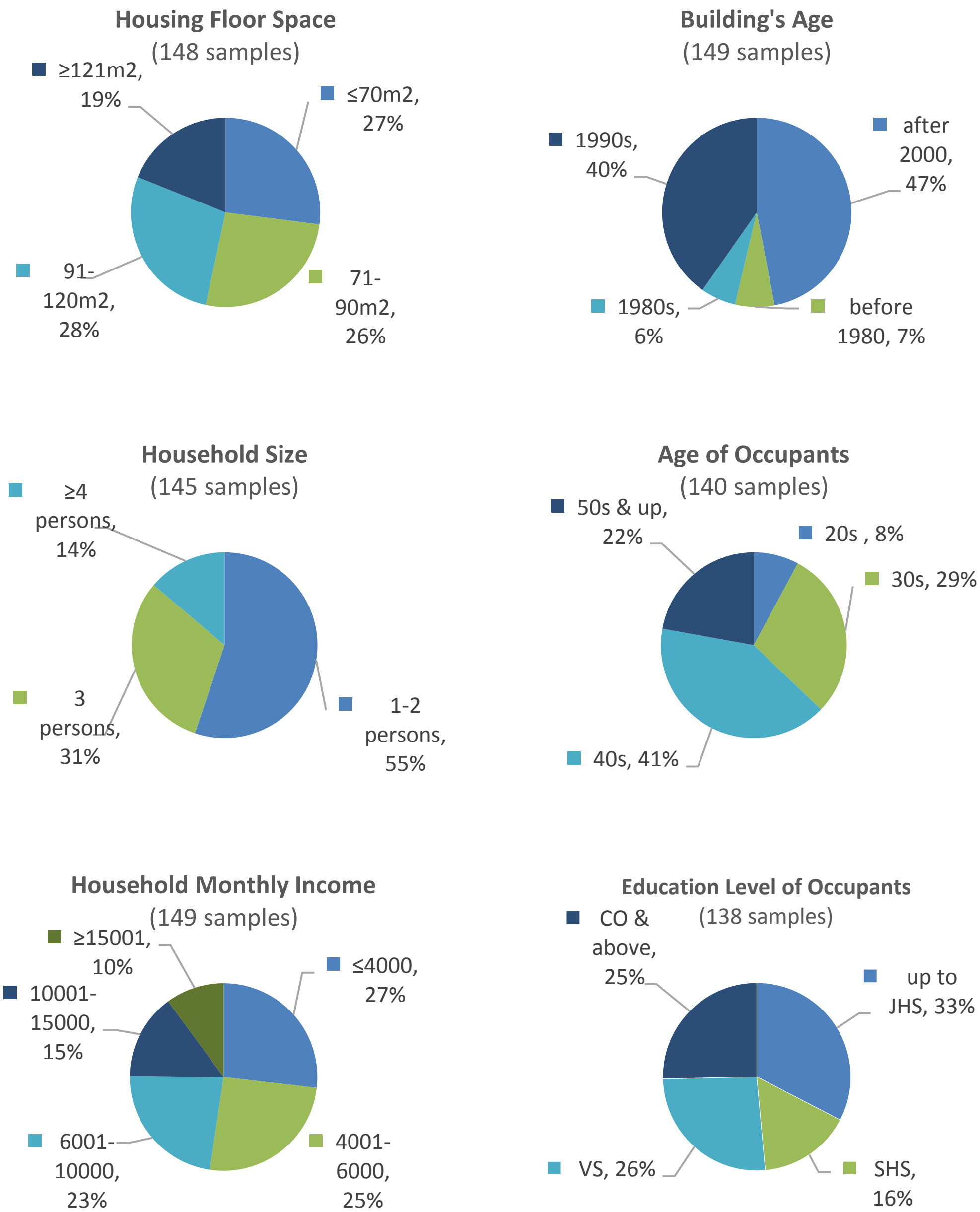
[60] There are in total six municipal districts in Xiamen (the other two Hai Cang and Xiang An), however these four core districts host the vast majority (about 83%) of Xiamen's population (XBS, 2011a).



Note: a) As for education level, JHS-junior high schools, SHS-senior high schools, VS-vocational schools, and CO-colleges; b) The age and education level of occupants are those of the main income-earners of the households.

Figure 4.2 Survey Samples Distribution in Key Household Features

(Source: Author's Household Energy Use Survey in Xiamen)

From Figure 4.2, it can be seen that the distribution of the survey samples are quite diversified in the four features (i.e., housing floor space, occupants' ages, household income, and occupants' education level). As for the buildings age, about 87% of surveyed households lived in buildings constructed after 1990. This distribution accurately reflects the reality in Xiamen. Based on statistical data from the Xiamen Bureau of Statistics[61] (XBS, 2011b), it is estimated that about 90% of Xiamen's current residential buildings were constructed within the past two decades (1990-2010). In addition, according to the XBS (2012b), the share of Xiamen households that comprise only 1-2 persons is about 54%. The survey samples were rather consistent with this fact. In summary, the survey samples are good representation of the general household structure in Xiamen.

In addition, of the total 150 surveyed households, 110 of them were home owners and the rest were tenants, which also accords with the current situation in most Chinese cities. According to the THUBERC (2013), about 30% of housing units in urban China are occupied by tenants.

To further check the representativeness of the survey samples, Table 4.2 presents a comparison of average housing floor space, average household size, and housing types between the survey samples and the XBS's (2012c, 2011a, 2003-2011) related statistics.

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[61] It is showed that the population in Xiamen doubled in the two decades from 1990-2010, and in the meantime the per capita housing floor space in the city had largely increased from about 7-8 m^2 in the early 1990s to 32.5 m^2 in 2011 (XBS, 2011b).

Table 4.2 A Comparison of Selected Housing Features between the Survey and the XBS Statistics

Housing Features		Sources	
		The Survey	**XSB Statistics**
Average Housing Floor Space (m^2/occupant)		40.8[1]	32.5[2]
Average Household Size (occupants/household)		2.30[1]	2.42[3]
Housing Pattern (%)	Low- or High-Rise Apartments	95.9	96.3[4]
	Attached or Detached Houses	0.7	1.0[4]
	Others (e.g., self-built bungalow)	3.4	2.7[4]

Note: [1] Data are from the 129 households that provided entire-year household energy consumption data in the survey; [2] Data are from the XSB's (2012c) "Xiamen Economic and Social Development Statistics Report 2011;" [3] Data are from the XSB's (2011a) "Bulletin of Xiamen's Population of the Sixth National Census;" [4] Data are from the XSB's (2003-2011) "Yearbook of Xiamen Special Economic Zone."

(Sources: Author's Household Survey in Xiamen; XBS, 2012c, 2011a, 2003-2011)

It can be seen that except for the average housing floor space, all the other key housing features accord with the survey conducted and the XBS's (2012c, 2011a, 2003-2011) statistics. As for the difference in average housing floor space, it must be noted that the XBS (2012c) statistics were based on only 300 household samples which are intentionally (not randomly) structured according to their household income[62] (namely, every 20% of households comes from a certain income group ranging from low to high). The difference in sampling methods may to some extent explain the relatively large gap of average housing floor space between the author's household survey and the XBS (2012c) statistics.

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[62] The primary purpose of the XBS for such sampling is showing the comparison among different income groups of households (XBS, 2012c).

4.1.2.2 Analysis of Survey Results

1. Total Household Energy Consumption

A total of 129 of the 150 surveyed households provided complete data of their household energy consumption for the year 2011. Based on the data, the distribution of Xiamen's average residential energy use intensity is shown respectively in Figure 4.3 (measured in per square meter) and Figure 4.4 (measured in per capita).

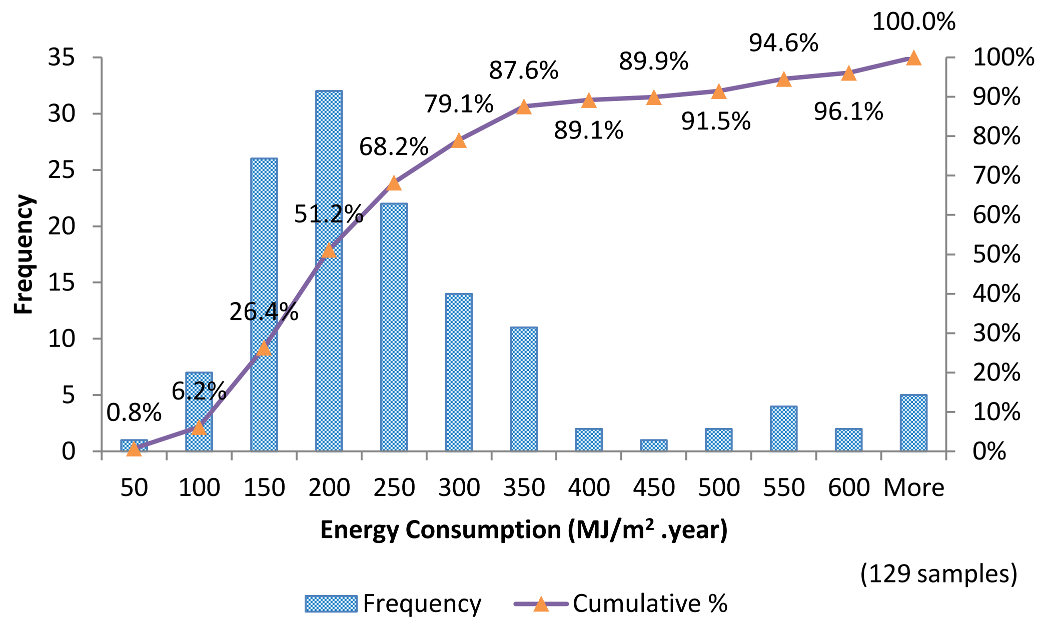

Figure 4.3 Residential Energy Intensity (per square meter) in Xiamen

(Source: Author's Household Energy Use Survey in Xiamen)

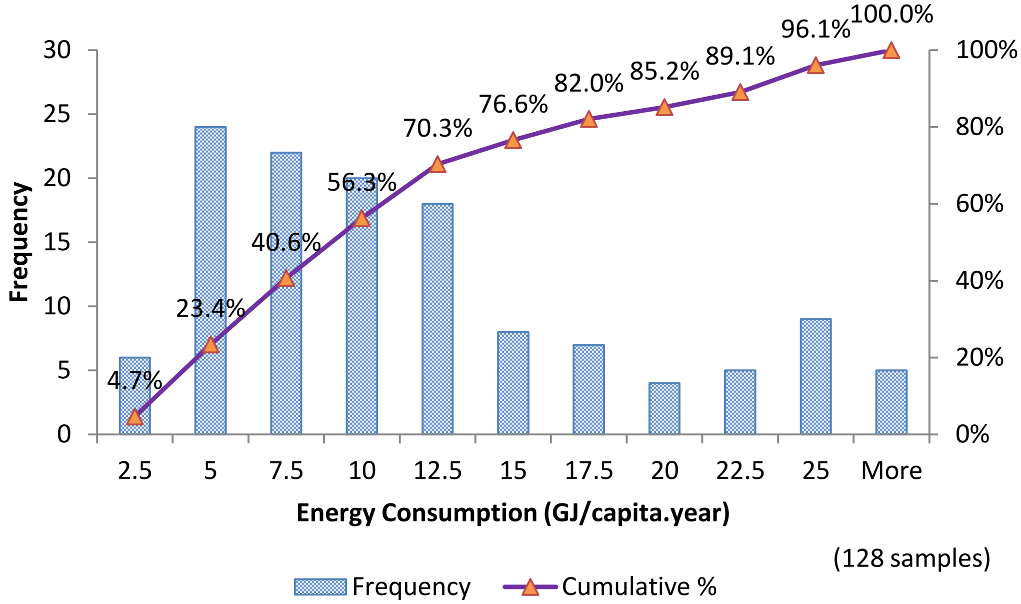

Figure 4.4 Residential Energy Intensity (per capita) in Xiamen

(Source: Author's Household Energy Use Survey in Xiamen)

On average, the residential energy consumption (REC) intensity in Xiamen is about 208 MJ/m^2 ·year or 8,483MJ/person ·year. However, there exists a large variation of REC intensity among Xiamen households, varying by a factor of about 8.3 (measured in per unit of housing floor space) or 12.3 (measured in per capita) between the highest 10% and lowest 10% of households. Such a huge REC intensity variation clearly shows the significant difference in energy use behaviors among occupants, and the huge energy-saving potential from changing people's behaviors as well.

2. Energy Consumption for Lighting

The survey shows that most Xiamen households have already adopted energy saving lamps (ESLs), such as fluorescent lamps, compact fluorescent lamps and light-emitting-diode (LED) lamps. About 81% of the surveyed households completely use ESLs; only 5% of them still use only incandescent lamps (ILs); the rest, 14% of households, simultaneously use both ESLs and ILs at home.

Table 4.3 summarizes the deployment and use patterns of lighting fixtures in Xiamen households. According to this, the energy consumption for lighting in Xiamen's residential buildings is estimated at about 272.6 kWh/household year.

Table 4.3 Deployment and Use Pattern of Lighting in Xiamen's Residential Buildings

Room Type	Average Installed Wattage (W)	Average Use Time (hours/day)	Rooms Coefficient[1]
Living Room	58	4.2	1.0467
Bedroom	45	3.1	2.3467
Study Room	27	2.4	0.3600
Dining Room	28	2.0	1.0467
Kitchen	18	1.9	0.9867
Bathroom	20	1.9	1.2622
Other Rooms (Storeroom, etc.)	14	2.1	0.0267

Note: [1] Room coefficient means the numbers of a certain type of room in a household on average.

(Source: Author's Household Energy Use Survey in Xiamen)

In China's *National Standard of Lighting Design for Buildings (GB 50034-2013* (SAC, 2013), the "lighting power density (LPD)" is adopted as a control index for evaluating the overall energy-saving performance of lighting. The LPD means the wattage of installed lighting fixtures per square meter[63]. Based on the survey data, the average LPD among Xiamen households is only about 1.8W/m^2, and the LPD for over 90% of the households is less than 3.0 W/m^2. In contrast, the LPD limit for residential buildings stipulated in the national standard GB 50034-2013 (SAC, 2013) is set to be 6.0 W/m^2 for current control and 5.0 W/m^2 for future control. Therefore, it can be seen that most households in Xiamen install lighting fixtures in moderation.

3. Energy Consumption for Cooking

According to natural gas consumption in those surveyed households that do not use gas-fired water heaters, the average residential energy consumption for cooking in Xiamen can be calculated at about 8,206 MJ/household·year (i.e., 215 m^3 natural gas/household·year), as shown in Figure 4.5.

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[63] It needs to be noted that the LPD index is not related to any certain lighting technologies. The given limits of LPD in China's national standard GB 50034-2013 were based on a comprehensive assessment of available lighting technologies at the time of designing the standard, and were proposed as a general control index for lighting design in buildings.

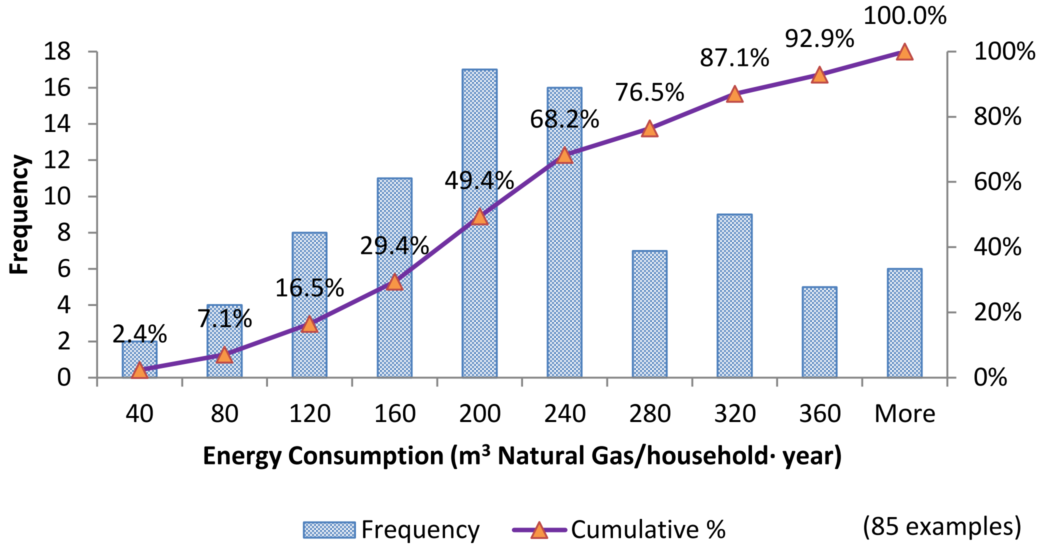

Figure 4.5 Energy Intensity for Cooking in Xiamen Households

(Source: Author's Household Survey in Xiamen)

Given the average household size (2.3 occupants/household) in the survey, the energy consumption intensity of cooking in Xiamen households is about 3,568 MJ/person·year. The THUBERC (2011) estimated an energy use intensity of 3,348/MJ·year for cooking in urban China. It can be seen that the values of these two intensities are quite close (with a gap of less than 7%), which is good proof of the credibility of the Xiamen survey data.

The survey shows that there are two basic types of gas cook stoves in Xiamen households, built-in type and desktop type. About 57% of the households adopt built-in type stoves. As for cooking frequency, it shows that about 54% of the households cook three times a day, 27% two times a day, and 19% one time or less a day.

4. Energy Consumption for Water Heating

According to the survey, about 77% of Xiamen's households use electric water heaters; 11% use gas-fired water heaters; 7% use solar water heaters; and 5% adopt centralized hot water systems. The survey also shows that hot water in Xiamen's households is mainly used for showering, and rarely (only reported by 4% of surveyed households) used for other purposes (such as bathing, laundry, room cleaning, etc.).

Based on the survey data of hot water demand per shower (about 52 liters through reading water meters before and after each shower in selected households) and shower frequency (5.3 times/person·week on all-year-around average), it is estimated that the demand of hot water in Xiamen is about 33,052 liters per household per year. According to Equation 4.3, given the average temperature of Xiamen's tap water (21 ℃[64]), and the surveyed distribution of various kinds of water heaters (the average thermal efficiency of gas-fired water heaters in Xiamen's households is about 88%), the energy consumption of water heating in Xiamen can be calculated as about 1,160 MJ/person·year (or 2,668 MJ/household·year).

5. Energy Consumption for Plug-in Appliances

In the survey, the detailed information on deployment (type, model size or capacity, energy efficiency tiers, nameplate wattage, etc.) and use patterns (frequency, time, schedule, etc.) of main plug-in appliances was carefully collected. Based on such information as well as the referential data of on-mode wattage[65] of some kinds of

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64 Almost all the tap water in Xiamen is from the Jiu Long River (i.e., surface water).

65 As mentioned before, such data are mainly obtained from the research (Ren and Hu, 2012) and testing reports on certain Chinese websites that focus on measuring the performance of appliances, including http://www.pconline.com.cn; http://www.ea3w.com/; http://www.zol.com.cn/, etc.

appliances (e.g., TVs and PCs), the average UEC of main appliances in Xiamen's households can be estimated reliably. Multiplying the UEC and ownership of appliances, the average electricity consumption of main appliances could be calculated, as shown in Table 4.4.

Table 4.4 Estimated Electricity Use of Main Household Appliances in Xiamen

Appliances	**Ownership[1]** (units/household)	**Use Patterns[1]**	**Average Electricity Consumption** (kWh/year household)
Refrigerators[2]	1.06	8760.0 hours/year	464.3
Rice cookers[3]	1.00	550 times/year	220.1
TVs[4][7]	1.14	1432.4 hours/year	213.9
PCs[5][7]	1.46	984.5 hours/year	138.0
Microwave ovens[3]	0.87	65.7 hours/year	74.3
Clothes Washers[6][7]	0.97	230 times/year	73.7
Irons[3]	0.29	59.4 hours/year	20.7

Note: [1] Obtained from the Xiamen survey; [2] The average electricity use is obtained from the energy use information (kWh/24hours) on the of refrigerators' energy labels; [3] The on-mode wattage are obtained from the nameplate wattage shown on these appliances' tags; [4] According to the survey, the distribution is about CCFL TV (61%), LED TV (22%), PDP TV (5%) and CRT TV (12%); [5] According to the survey, the distribution is about 61% for desktops and 39% for laptops; [6] According to the survey, the distribution is about 78% for top-loading type and 22% for front-loading type; [7] First, the average "size or capacity" of these appliances were identified from the survey; Then, through referring to the research (Ren and Hu, 2012) and testing reports on certain Chinese websites (see the data sources), an average on-mode wattage is given to each of these appliances: CCFL TVs (143W), LED TVs (89W), PDP TVs (250W), CRT TVs (100W), Laptop PCs (35W), Desktop PCs (34.5W for monitor and 100W for all the other parts), top-loading type clothes washers (0.102kWh/time), front-loading type clothes washers (1.14kWh/time).

(Sources: Based on Author's Household Energy Use Survey in Xiamen; Ren and Hu, 2012; Testing reports of electricity use of appliances on the websites of http://www.pconline.com.cn, http://www.ea3w.com/, and http://www.zol.com.cn/)

According to Table 4.4, the overall electricity consumption intensity of these main plug-in appliances (measured in per unit housing floor space) is about 12.85 $kWh/m^2 \cdot year$.

6. Energy Consumption for Space Cooling

Much of the key information related to space cooling in Xiamen's households was obtained from the survey. First, space cooling in Xiamen's residential buildings relies completely on room ACs[66]; second, the AC ownership in Xiamen is about 2.38 units/household on average (a total of 357 AC units were installed in the 150 surveyed households); third, about 80% of these installed AC units are split-type, while the rest 20% of units are window-type; fourth, among the installed 357 AC units, 319 of them are fixed-speed air conditioners (FSACs), while the rest are variable-speed air conditioners (VSACs).

The THUBERC (2013) summarized a number of research results on space cooling energy use intensity in China, and reported that such an intensity in China's HSWW climate zone in which Xiamen belongs is about 7.9 $kWh/m^2 \cdot year$. In this dissertation, this value is adopted as the average space cooling energy consumption intensity in Xiamen households.

7. Mapping Xiamen's Residential Energy Consumption Patterns

Substituting the above achieved six energy consumption intensities into Equation 4.1, it can be seen that the value of the Equation's left side is about 1.93

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[66] For our surveyed households in Xiamen, no centralized space cooling systems were used.

$kWh/m^2 \cdot year$ larger than that of the Equation's right side. As presented in Section 4.1.1.2, such a gap represents the electricity consumption intensity of the plug-in appliances which are not included in Table 4.4. Therefore, through adding back the intensity of "1.93 $kWh/m^2 \cdot year$" to the previously calculated intensity of "12.85 $kWh/m^2 \cdot year$," it is estimated that the final electricity consumption intensity of plug-in appliances in Xiamen's households is about 14.78 $kWh/m^2 \cdot year$. It can be seen that the plug-in appliances which are not listed in Table 4.4 may account for only about 10.3% of the total electricity use by household plug-in appliances.

The energy consumption intensities of the five basic end-use groups in Xiamen's residential buildings are summarized in Table 4.5. For the purpose of comparison, all these intensities are also presented in a uniform unit of $MJ/m^2 \cdot year$.

Table 4.5 Energy Consumption Intensity in Xiamen Households by End Uses

End Use	Surveyed Final Energy Consumption	Energy Use Intensity (MJ/m^2.year)	Percentage
Cooking	215m^3 natural gas/household·year	87.4[1]	42.0 %
Lighting	272.6 kWh/ household·year	10.5	5.0 %
Plug-in Appliances	1,386.4 kWh/household·year	53.2	25.6 %
Water Heating	2,668 MJ/household·year	28.4	13.7 %
Space Cooling	7.9 $kWh/m^2 \cdot year$	28.5	13.7 %
	Total	**208.0**	**100 %**

Note: [1] The calorific value of natural gas used in Xiamen is about 38.17MJ/m^3.

(Sources: Author's Household Energy Use Survey in Xiamen; THUBERC, 2013)

From Table 4.5, it can be seen that cooking, with a share of over 40%, is the biggest energy end-use in Xiamen's residential buildings, followed by plug-in appliances (25.6%), space cooling (13.7%), and water heating (13.7%). Owing to the high penetration of ESLs, lighting in Xiamen's residential buildings consumes the smallest share of energy, only about 5%. In total, a Xiamen household, on average, consumes about 19.5GJ of energy annually.

In order to further check the validity of the calculated energy consumption in Table 4.5, as discussed before a cross-check of electricity consumption intensity (ECI) in Xiamen's residential buildings was implemented. According to the author's survey, Xiamen's residential "*ECI*" is equal to the total of energy consumption intensity of lighting, plug-in appliances, space cooling and part of the water heating (77% Xiamen households using electric water heaters reveled by the survey), which is calculated as about 31.6 $kWh/m^2 \cdot year$ based on the data in Table 4.5. On the other hand, according to the XBS's macro statistics of average residential electricity consumption and per capita housing floor space in 2011 (XBS, 2012a), the residential "*ECI*" in Xiamen is about 29.0 $kWh/m^2 \cdot year$. Two "*ECI*" are quite in accordance with each other (with only a small gap of about 9%). This cross-checking shows the reliability of the survey data and the credibility of the adopted survey analysis methods.

Based on the above analysis, the energy consumption patterns in Xiamen's residential buildings are presented in Figure 4.6. Such patterns represent the baseline energy consumption levels in Xiamen's households, which are the crucial and fundamental data for implementing energy-saving potential analysis in the City.

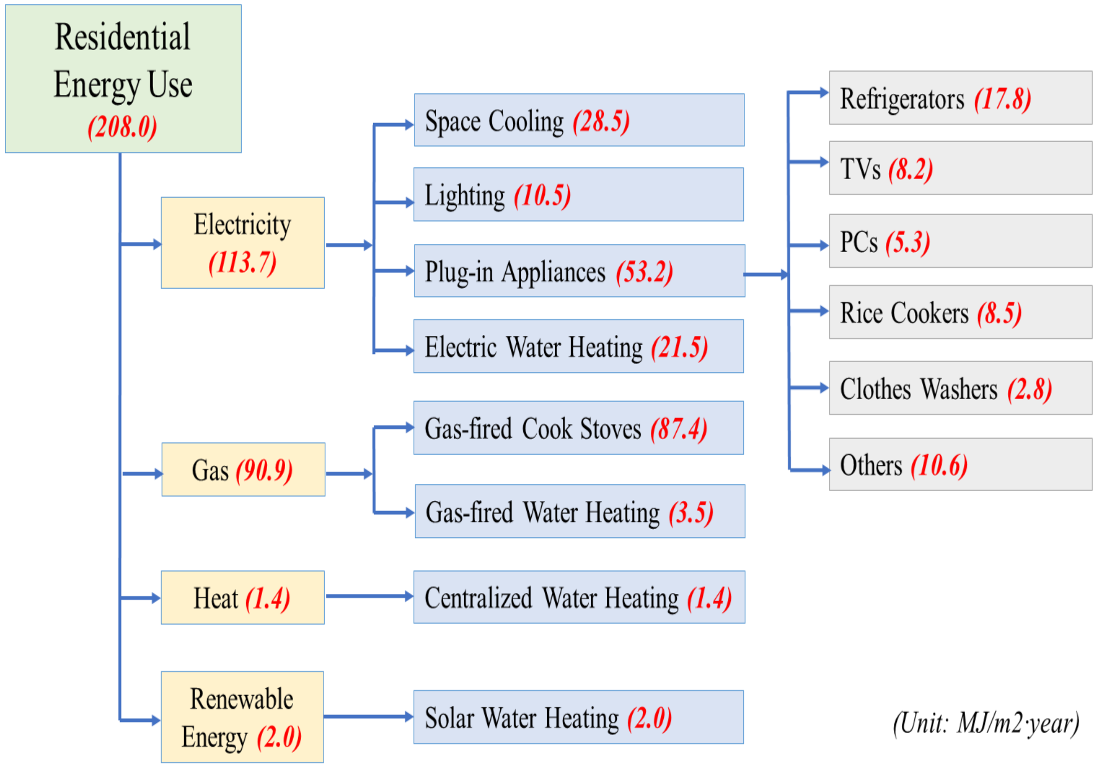

Figure 4.6 Energy Consumption Patterns in Xiamen's Residential Buildings

(Sources: Author's Household Energy Use Survey in Xiamen; THUBERC, 2013)

4.2 Energy-Saving Measures for Xiamen's Residential Buildings

From Figure 4.6, it can been seen that among the four types of energy supply to Xiamen's households, heat and renewable energy account for only a very tiny share of total household energy consumption (about 1.6% combined). Accordingly, this research focuses primarily on the analysis of energy-saving potential from the use of electricity and natural gas[67].

In addition, as shown in Table 4.5, the end-use of lighting accounts for only a very small share (about 5%) of final energy consumption in Xiamen's residential buildings. Given that most of Xiamen households have already completely adopted energy efficient lamps at home (over 80%), it is reasonable to assume that little energy-saving potential can still be achieved from upgrading lighting in Xiamen's residential buildings. Therefore, this research focuses on energy-saving measures in the other four energy-end uses: space cooling, plug-in appliances, cooking and water heating. The selected feasible energy-saving measures for Xiamen's residential buildings are listed in Table 4.6.

[67] As discussed in Chapter 2, the application of solar water heaters in Chinese cities is largely restricted by the limited roofs space of residential buildings mainly because of the dominance of high-rise apartment buildings in urban China. Thus, significantly expanding the current 7% penetration of solar water heaters in Xiamen households will be rather difficult. In addition, because of the low demand of hot water in Chinese households (mostly only for showering), the centralized water heating systems are seldom adopted in urban China due to the low cost-effectiveness.

Table 4.6 Residential Energy-Saving Measures Selected for Xiamen

Energy End Use	Selected Energy-Saving Measures
Space Cooling	Retrofitting building envelopes to reduce space cooling load[1]
	Adopting energy efficient air conditioners
Plug-in Appliances[2]	Adopting energy efficient refrigerators
	Adopting energy efficient TVs
	Adopting energy efficient PCs
	Adopting energy efficient rice cookers
	Adopting energy efficient clothes washers
Water heating	Adopting energy efficient electric water heaters
	Adopting energy efficient gas-fired water heaters
Cooking	Adopting energy efficient gas-fired cook stoves

Note: [1] Retrofitting building envelopes actually includes a lot of sub-measures, and the appropriate and effective sub-measures for the Xiamen case are discussed in details in Section 4.3.1; [2] As for plug-in appliances, this research focuses only on five important types (refrigerators, TVs, PCs, rice cookers, and clothes washers), which together account for about 80% of the total electricity consumption of plug-in appliances in Xiamen's residential buildings according to the survey.

(Source: Based on Author's Household Energy Use Survey in Xiamen)

4.3 Market Survey of Available Advanced Energy-Saving Measures

As shown in Chapter 3, in addition to the data on current residential energy use patterns, the data on the efficiency levels and related incremental costs of advanced energy-saving measures are also crucial for the energy-saving potential analysis. Such required data can be obtained through "market surveys" in which the price-efficiency relationship of various household energy use equipment is analyzed.

As for the Xiamen case study, the data on prices and energy efficiency of household energy use equipment which are currently available in the Chinese market were collected mainly through the official website of SUNING (2014)[68] – one of the biggest online appliances dealers in China.

Before the analysis of price-efficiency relationship, the energy efficiency (efficacy) level (EEL) indicator for each energy-saving measure needs to be identified first because it is very measure-specific. The related values of these adopted EEL indicators should be achievable under the current information disclosure situation in China. The average EEL of the stock of current measures in Xiamen's residential buildings (which are collected from the Xiamen Household Energy Use Survey) are also presented in this section.

The market survey results are presented in the following sub-sections.

4.3.1 Building Envelope Retrofitting

The primary purpose of retrofitting a building's envelope is to reduce its energy consumption for space heating and cooling. Therefore, for the Xiamen case where space heating is almost not needed, the buildings' annual cooling load is the most appropriate EEL indicator for the measure of building envelope retrofits. Therefore, the energy efficiency gap (i.e., "EEG_{BE}") of upgrading the building envelope from the baseline level could be calculated as follows[69]:

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[68] The data were collected in September 2014.

[69] The "EEG" for all the appliances in this research means the percentage (%) of energy saved from the baseline energy consumption level.

$$EEG_{BE} = 1 - (\frac{BCL_1}{BCL_0}) \qquad (4.4)$$

where *"BCL_0"* and *"BCL_1"* respectively stand for the "annual accumulated space cooling load" before and after upgrading a building envelope.

Given the climate characteristics of Xiamen, Table 4.7 summarizes the most feasible retrofitting measures for Xiamen's residential buildings based on related research (Cai, 2006; Zhou et al., 2010).

Table 4.7 Retrofitting Measures Recommended for the Residential Buildings in Xiamen

Building Envelope	**Current Measures**	**Suggested Retrofitting Measures**
Walls	110mm reinforced concrete (K=3.3)	Adding 20mm XPS insulation layer (K=0.87)
Roofs	180mm porous clay brick (K=2.1)	Adding 200mm aerated concrete insulation layer (K=0.81)
Windows	6mm ordinary single glazing (Sc=0.7)	Replaced by coated insulating double glazing (Sc=0.5)

Note: a) XPS means extruded polystyrene board; b) "K" means the "heat transfer coefficient" in units of $W/m^2 \cdot K$; c) "Sc" means overall window shading coefficient (unitless); d) There are no "K" value requirements for the windows of buildings in HSWW zone.

(Sources: Zhou et al., 2010; Cai, 2006)

In Table 4.7, the "current measures" stand for the popular envelope construction of Xiamen's residential buildings which were constructed during the 1990s and 2000s (accounting for almost 90% of the current stock of residential buildings in the city), while the "retrofitting measures" are in compliance with the latest building energy code of JGJ75-2012 (Zhou et al., 2010; Cai, 2006). The reduction of cooling loads after adopting these three retrofitting measurers in Xiamen's residential buildings was evaluated through a simulation calculation[70] (Cai, 2006). The simulation results are shown in Figure 4.7. It can be seen that the retrofits of walls, roofs and windows in Xiamen's residential buildings could respectively contribute to a reduction of a building's cooling load by about 2.5%, 8.8% and 32.0% from the baseline level (Cai, 2006).

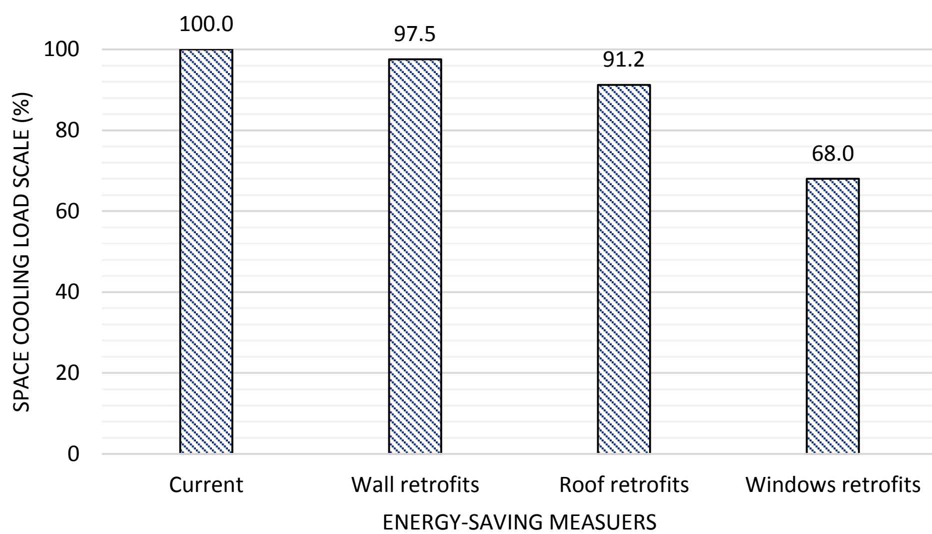

Figure 4.7 Reduction Scale of Space Cooling Load from Retrofitting Building Envelope in Xiamen

(Source: Cai, 2006)

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70 *DeST* software was used for this simulation. *DeST* is a verified simulation software of buildings' energy performance, similar to the *EnergyPlus* or *eQUEST* in the U.S.

Compared with the measurers of retrofitting roofs and windows, the cooling load cut from retrofitting walls is relatively small in Xiamen. The main reason is that well-insulated walls in Xiamen could significantly impede the natural indoor-outdoor heat transfer through walls at night which may cause an increase in cooling demand at night. Actually, given Xiamen's local climates the most effective way to reduce the cooling load of buildings in the city is to cut down unnecessary heat gains from solar radiation (THBERC, 2013), which explains why retrofitting roofs and windows are much more effective. Accordingly, in this research upgrading buildings roofs and windows are selected as the appropriate technical measures for retrofits in Xiamen's residential buildings.

The related incremental cost for such envelope retrofits are also analyzed in the research of Zhou et al. (2010) - about 6 Yuan/m^2 for upgrading roofs and 85 Yuan/m^2 for upgrading windows. It must be noted that the "m^2" here means the floor space of buildings but not the space of roofs or windows.

4.3.2 Air Conditioners

Currently, there are two basic types of room air conditioners in China: fixed-speed air conditioners (FSAC), and variable-speed air conditioners (VSAC). The FSAC units' compressors can operate only at a certain single speed no matter what the cooling load levels are[71]. Conversely, the compressors of VSAC units are able to precisely match system capacity to the actual load. In this way, the VSAC units can always keep high energy efficiency in operation, especially compared to the fixed-speed ones.

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[71] The speed is set to maximum the energy efficiency of an FSAC unit in its full capacity operation.

The energy efficiency of FSAC and VSAC units is respectively stipulated in the national standards of GB 12021.3-2010 and GB 21455-2013 (Energy Label, 2014). In these national standards, the EEL indicator for FSAC units is "Energy Efficiency Ratio (EER)" meaning the ratio of output cooling energy to input electrical energy, while for VSAC units, it is "Seasonal Energy Efficiency Ratio (SEER)" defined as total cooling output divided by total electric energy input during a typical cooling season[72]. Therefore, the EEG from adopting efficient FSAC and VSAC units (namely "EEG_{FSAC}" and "EEG_{VSAC}" respectively) can be calculated as follows:

$$EEG_{FSAC} = 1 - (\frac{EER_0}{EER_1}) \qquad (4.5)$$

$$EEG_{VSAC} = 1 - (\frac{SEER_0}{SEER_1}) \qquad (4.6)$$

where "EER_0" and "EER_1" are respectively the "*EER*" of current and efficient FSAC units; "$SEER_0$" and "$SEER_1$" are respectively the "*SEER*" of current and efficient VSAC units.

Due to the relatively small floor space of rooms (usually 10-30 m^2 per room), the cooling capacity of air conditioners in Xiamen households is mostly either 3,500W or 2,300W (almost equally distributed) according to the author's survey in Xiamen. Therefore, the EEL of the AC units with these two kinds of cooling capacity are targeted for the market survey in this research.

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72 The definitions of both the "EER" and "SEER" are the variations of the popularly-used term of "coefficient of performance (COP)" in thermodynamics. Larger EER or SEER means more efficient.

The Chinese classification of energy efficiency tiers for the FSAC and VSAC with the cooling capacity less than 4,500W is summarized in Table 4.8 and 4.9.

Table 4.8 Energy Efficiency Labelling for FSAC in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**		
		Tier-1	Tier-2	Tier-3
Cool Capacity ≤ 4,500W	EER (W/W)	3.6	3.4	3.2

(Source: GB 12021.3-2010 on Energy Label, 2014)

Table 4.9 Energy Efficiency Labelling for VSAC in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**		
		Tier-1	Tier-2	Tier-3
Cooling Capacity ≤ 4,500W	SEER (W/W)	5.4	5.0	4.3

(Source: GB 21455-2013 on Energy Label, 2014)

However, it must be noted that the "*EER*" and "*SEER*" cannot be compared directly because of the different testing methods used for them. According to research (Xu and Liao, 2008), the "*EER*" of FSACs would increase by about 0.6 (0.57-0.64) when adopting the "*SEER*" testing method. Thus, to make "*EER*" and "*SEER*" comparable, such an efficiency correction is adopted in this research for later technical potential analysis of energy savings[73]. According to the Household Energy Use

[73] The realistic operating environment of an air conditioner is more like the one for testing SEER; therefore, in this research the efficiency correction is implemented by enlarging the EER to equivalent SEER.

Survey in Xiamen, it was found that the average "*EER*" for the FSAC units installed in Xiamen is about 3.0, while the average "*SEER*" for the VSAC units in Xiamen is about 3.9.

Based on the energy efficiency and price data on the SUNING website[74], it is found that there is a noticeable rise in average price along with the efficiency improvement of AC units (for both FSAC and VSAC). The related price data are shown in Table 4.10.

Table 4.10 Average Prices of Room Air Conditioners in China

Model Type	**FSAC**			**VSAC**		
	Tier-3	Tier-2	Tier-1	Tier-3	Tier-2	Tier-1
Average Price[1] (Yuan/unit)	2,116	2,723	5,077	3,100	4,419	6,374
Incremental Cost (Yuan/unit)	Baseline[2]	+ 607	+ 2,961	+ 984	+ 2,303	+ 4,258

Note: [1] The price was collected as of September 2014, and weighted by the units with cooling capacity of 3,500W and 2,300W; [2] Tier-3 FSAC has the lowest efficiency, and is then the baseline option for consumers.

(Source: Author's statistics based on SUNING, 2014)

Based on the market survey, the energy efficiency tier distribution of the FSAC and VSAC models available in the Chinese market can also be obtained, shown in

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74 A total of 282 available AC models from twenty-one manufacturers (brands) are covered in the market survey, including 54 FSAC models of CC=3,500W, 43 FSAC models of CC=2,300W, 99 VSAC models of CC=3,500W, and 86 VSAC models of CC=2,300W.

Figures 4.8 and 4.9 respectively. It can be seen that only a small proportion of air conditioners in the Chinese market could reach the Tier-1 efficiency, representing about 4% of FSAC models and 14.3% of VSAC models.

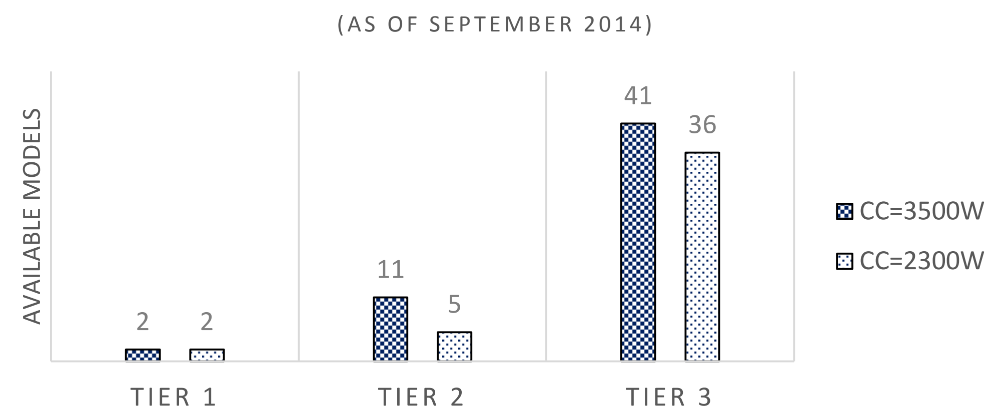

Figure 4.8 Energy Efficiency Distribution of FSAC Models in China

(Source: Author's statistics based on SUNING, 2014)

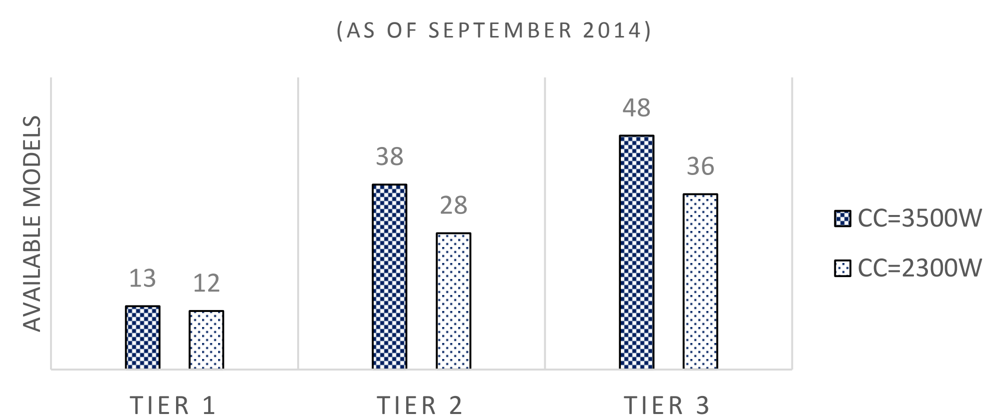

Figure 4.9 Energy Efficiency Distribution of VSAC Models in China

(Source: Author's statistics based on SUNING, 2014)

4.3.3 Refrigerators

There are four basic types of refrigerators in the Chinese market, namely BC-type, BD-type, BC/BD-type, and BCD-type[75]. Almost all Chinese households use the BCD-type units (CLASP, 2013).

According to China's EES&L scheme for refrigerators (GB12021.2-2008), the daily electricity consumption must be shown on the energy label of each refrigerator. Given the operation mode of refrigerators (24 hours), the EEG from adopting efficient refrigerators (namely *"EEG_{RF}"*) can be calculated as follows:

$$EEG_{RF} = 1 - ES_1/ES_0 \qquad (4.7)$$

where *"ES_0"* and *"ES_1"* respectively stand for the daily electricity consumption of current and efficient refrigerators.

According to the author's household survey in Xiamen, most of the refrigerators (approximate 90%) are two-door BCD type (i.e., the often-called "fridge-freezer" type) with a store volume ranging from 160 to 220 liters (180 liter/unit on average). Therefore, in this research the refrigerator with a store volume of around 180 liter is used as the typical model for the analysis of the price-efficiency relationship. In addition, a statistical analysis of the energy label information on existing refrigerators in Xiamen found that the average electricity use from refrigerators in the city is about 1.2 kWh/day in 2011.

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[75] The classification is defined as BC-type (only for storing fresh food), BD-type (for storing only frozen food), BC/BD-type (having compartments which can be shifted to store fresh or frozen food but not both at the same time), and BCD-type (having compartments which can be used to store fresh and frozen food at the same time).

Based on the energy efficiency and price data on the SUNING website[76], it is found that the energy efficiency of related refrigerator models (around 180-liter volume) can be separated into two distinct groups[77]: one baseline group with the electricity use about 0.47-0.49 kWh/day, and one advanced group with the electricity use about 0.37-0.39 kWh/day. The average prices of the baseline group and advanced group are about 1,420 Yuan/unit and 1,675 Yuan/unit respectively, which represents an incremental cost of about 255 Yuan/unit.

4.3.4 TVs

There are three basic types of TVs in Chinese households, namely CRT (cathode ray tube) TVs, LCD (liquid crystal display) TVs and PDP (plasma display panel) TVs. Due to the differences in backlighting technologies, the LCD TV can be further divided into two sub-types, namely, CCFL (cold cathode fluorescent lamp) TVs and LED (light emitting diodes) TVs.

The Chinese TV market was fully dominated by CRT TVs before 2000. However, the current dominant role is now played by LED TVs which emerged for sale in China in 2009 (CLASP, 2013). The PDP and CCFL TV (available for sale since 2002) have gradually been proven to be less competitive on thickness, durability and energy efficiency than LED TVs during the past years, and, as a consequence,

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[76] A total of 17 models (with a volume between 175 and 189 liters) from the nine most popular brands in China are covered in the market survey, including the brands of Haier, Siemens, Ronsheng, Xinfei, Meiling, Whirlpool, Hisense, Media, and Electrolux.

[77] The EEL indicator stipulated in the national standard GB12021.2-2008 for refrigerators is the "η" - meaning a percentage to a certain virtual energy use level, which is not appropriate for the EEG calculation in this research.

both of them are almost not available for sale in urban China. According to the collected information from the SUNING website (as of September 2014), of the total 802 available TV models in China, only 7 models are PDP TVs[78], and all the other are LED TVs. Therefore, in this research the LED TV is considered the only option for the purchases of TVs for Xiamen's consumers.

The EEL indicator of LCD TVs is stipulated in China's national standard GB 24850-2010 called "Energy Efficiency Index (EEI)." The calculation of "*EEI*" is as follows:

$$EEI_{LCD} = \left[\frac{L \times S}{P_k - P_s}\right] / 1.1 \qquad (4.8)$$

where "EEI_{LCD}" stands for the "*EEI*" of LCD TVs; "L", "S" and "P_k" respectively stand for the average screen luminance, screen size, on-mode wattage of TVs; "P_s" stands for TVs' power wattage to process signal (usually 17 W when digital radio frequency interface is applied according to the GB 24850-2010).

Therefore, the EEG from adopting high-efficiency LED TVs (namely "EEG_{TV}") can be estimate as follows:

$$EEG_{TV} = 1 - \frac{EEI_0}{EEI_1} - \frac{17 \times (EEI_1 - EEI_0)}{EEI_1 \times P_k^0} \qquad (4.9)$$

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[78] In fact, almost all the largest PDP TV manufactures in the world have decided to shut down their PDP TV business entirely (such as Panasonic in 2013, Samsung and LG in 2014).

where *"EEI_0"*, *"EEI_1"* and *"P_k^0"* respectively stand for the "*EEI*" of current TVs, the "*EEI*" of efficiency-advanced TVs, and the on-mode power wattage of current TVs.

According to the household survey in Xiamen, the most popular LCD TV sizes are generally of two kinds, 32-inch (usually put in bedrooms) and 42-inch (usually put in living rooms). Therefore, these two sizes of TVs are targeted in the market survey. In addition, based on a statistical analysis of the information found on energy labels of TVs, the household survey found that the average "*EEI*" in Xiamen is about 0.84 for CCFL TVs, and 1.47 for LED TVs. Table 4.11 shows the current classification of energy efficiency tiers for LCD TVs in China.

Table 4.11 Energy Efficiency Labelling for TVs in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**		
		Tier-1	Tier-2	Tier-3
LCD TV	Energy Efficiency Index (unitless)	2.7	2.0	1.3

(Source: GB 24850-2013 on Energy Label, 2014)

However, it must be noted that the "*EEI*" calculation in the two versions of the national standard (namely GB24850-2010 and GB2485-2013) differ. As the author's household survey in Xiamen was implemented in 2012, the "*EEI*" values collected from the survey need to be converted in order to be comparable to the "*EEI*" stipulated in the new version of standard (GB2485-2013). With such a conversion[79], the "*EEI*" of 2.7 in the new standard is actually equal to the "*EEI*" of 3.1 in the old standard[80].

Moreover, based on the energy efficiency and price data on the SUNING website[81], there is no significant price increase corresponding to the efficiency improvement of LED TVs in China. This finding is rather consistent with the observation in the CLASP's 2013 research of *Market Analysis of China Energy Efficient Products*, quoted below:

> *There is actually very little relationship between price and EET (EE Tiers for TVs). This is contrary to the common perception that more efficient products are more expensive. The reason for this is most likely that energy efficiency is not the primary focus for consumers. Hence, manufacturers price products based on other criteria such as picture quality, 3D capability, interactive control, and network connectivity. These functions or attributes tend to be more expensive to incorporate in the product than efficiency, and this impact outweighs the costs of any energy efficiency attributes affecting the product price (CLASP, 2013: 114).*

Therefore, in this research it is assumed that there is no incremental cost for adopting more efficient LED TVs for Xiamen consumers. In this sense, the key for

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79 The conversion equation is $EEI_{new} = EEI_{old} \times (P_k - 17) \times 1.1 / P_k$, where "$P_k$" is the on-mode wattage of TVs (CLASP, 2013).

80 This is calculated as a weighted average of "2.93 for 42 inch TVs" and "3.42 for 32 inch TVs" according to the shares of these two sizes of TVs in Xiamen's households (65% of 42 inch TVs and 35% of 32 inch TVs).

81 In total, eighty-seven TV models from twelve brands are surveyed, including 27 models with the screen size of 32 inches and 60 models with the screen size of 42 inches.

promoting the adoption of high-efficiency LED TVs may be mainly on the production side rather than consumption side – namely, heavily dependent on the manufacturers' willingness and attention given to the efficiency improvements of their TV products. Accordingly, issuing more stringent EES&L scheme for TVs might be quite effective in promoting the penetration of efficient TVs. The Chinese government may have already understood this fact as it revised the 2010 EES&L scheme for TVs in 2013, quite a short revision cycle of only 3 years particularly compared to the usual 5-9 years for other appliances.

4.3.5 Rice Cookers

Because of the typical Chinese diet, the rice cooker is an important appliance in Chinese households, particularly in southern China. According to the CLASP (2013), almost all the rice cookers in China (about 98%) adopt electrical resistance heating technology[82].

The EEL indicator of rice cookers is stipulated in the national standard GB 12021.6-2008 as the thermal efficiency "η" of rice cookers. Therefore, the EEG from adopting efficient rice cookers (namely "EEG_{RC}") can be calculated as follows:

$$EEG_{RC} = 1 - \eta_0/\eta_1 \qquad (4.10)$$

where "η_0" and "η_1" stand for the thermal efficiency of current and energy efficient rice cookers respectively.

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[82] Resistance heaters produce heat by passing an electric current through a resistance, which impedes current and causes it to give off heat.

The author's household survey found that the power capacity of rice cookers in Xiamen is usually within the range of 400-600W and their average thermal efficiency is about 80.8% according to a statistical analysis of related information on these rice cookers' energy labels. In this research, rice cooker models with a power capacity between 400W and 600W were used for the market survey.

The classification of energy efficiency tiers for rice cookers in China is summarized in Table 4.12. The Tier-1 efficiency is actually quite stringent, as the CLASP (2013) showed that only 1% of the available models could reach this level of thermal efficiency.

Table 4.12 Energy Efficiency Labelling for Rice Cookers in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**				
		Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
400W < P ≤ 600W	Thermal Efficiency (η)	86%	82%	77%	73%	61%

Note: "P" stands for the power capacity of rice cookers.

(Source: GB 12021.6-2008 on Energy Label, 2014)

As the energy efficiency data of rice cookers are not available on the SUNING website, it is impossible to make an analysis of price-efficiency relationship for rice cookers through a market survey. However, the CLASP (2013) analyzed such a relationship (for rice cookers with the same volume), and found that there is no significant positive correlation between the efficiency and price of rice cookers. Therefore, it concluded that upgrading the energy efficiency tier thresholds for rice cookers would not adversely affect the products price. Accordingly, as with TVs, this research assumes that no incremental cost would accompany high-efficiency rice cookers in China.

4.3.6 Clothes Washers

There are two basic types of clothes washers in the Chinese market, namely the top-loading type (also called impeller-type) and the front-loading type (also called drum-type). Compared to the top-loading type, the front-loading type washers usually consume much more electricity for the same amount of laundry load[83]. Since they are viewed as fashionable and provide households with some flexibility in utilizing the space above the washers, front-loading type washers are becoming preferred by Chinese households.

The EEL indicator of clothes washers is stated in the national standard of GB 12021.4-2013 as "Electricity Consumption Level (ECL)" in units of kWh per kilogram laundry per washing cycle. Therefore, the EEG from adopting efficient clothes washers (namely *"EEG_{CW}"*) can be calculated as follows:

$$EEG_{CW} = 1 - ECL_1/ECL_0 \qquad (4.11)$$

where *"ECL_0"* and *"ECL_1"* respectively stand for the "*ECL*" of current and efficient clothes washers.

Due to household size (2-3 occupants/household) in Xiamen, the household survey found that the loading capacity of clothes washers in the City is mostly about

83 One of the advantages of front-loading type clothes washers is their lower water use than top-loading type ones.

6-7 kilograms (kg). Therefore, washers with this loading capacity were targeted for the market survey. Based on the information on the energy labels of clothes washers in Xiamen's households, it was found that the average "*ECL*" of Xiamen's clothes washers stock is about 0.017 (in units of kWh per kg laundry per washing cycle) for top-loading type, and 0.19 for front-loading type respectively.

The classification of energy efficiency tiers for clothes washers in China are summarized in Table 4.13.

Table 4.13 Energy Efficiency Labelling for Clothes Washers in China

Model	Energy Efficiency Indicator	Energy Efficient Tiers				
		Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
Top-loading	Electricity Consumption Level (kWh per kg laundry per washing cycle)	0.011	0.012	0.015	0.017	0.022
Front-loading		0.11	0.13	0.15	0.17	0.19

(Source: GB12021.4-2013 on Energy Label, 2014)

Based on the energy efficiency and price data on the SUNING website[84], the energy efficiency tier distribution of clothes washers and the incremental cost for adopting efficient models can be obtained. These are shown respectively in Figure 4.10 and Table 4.14.

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[84] A total of 193 available models of clothes washers with loading capacity of 6-7kg are surveyed. These models are from eighteen brands, and include 84 top-loading models and 109 front-loading models.

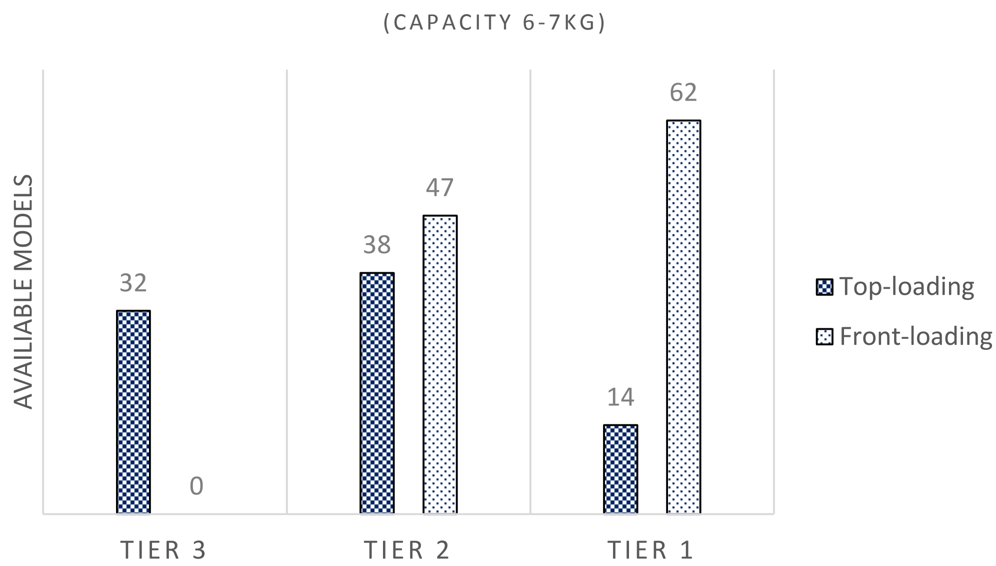

Figure 4.10 Energy Efficiency Distribution of Clothes Washers in China

(Source: Author's statistics based on SUNING, 2014)

From Figure 4.10, it can be seen that all the front-loading type washers are Tier-1 (about 57%) and Tier-2 (about 43%) products. In comparison, only about 17% top-loading type washers are labeled as Tier-1 products. Such a fact implies that the energy efficiency standard for top-loading type washers may be to some extent weak, and should be tightened. In addition, it needs to be noted that although the Chinese EES&L scheme for clothes washers are designed to be five tiers, the products with lower efficiency tiers are actually not available in the Chinese market (i.e., Tiers-4 and 5 top-loading type products and Tiers-3, 4 and 5 front-loading type products).

Table 4.14 Average Prices of Clothes Washers in China

Model (Capacity: 6-7 kg)	Energy Efficiency Tiers				
	Top-loading Type			Front-loading Type	
	Tier-3	Tier-2	Tier-1	Tier-2	Tier-1
Average Price[1] (Yuan/unit)	1,447	1,455	2,639	2,774	3,555

Note: [1] The price was collected as of September 2014.

(Source: Author's statistics based on SUNING, 2014)

Table 4.14 shows that for top-loading washers the prices of Tier-2 and Tier-3 products are almost the same. To simplify the analysis, these two tiers are combined into one tier, and the average price and efficiency of them are used for the potential analysis. Therefore, the incremental cost for Tier-1 washers is about 1,188 Yuan/unit for top-loading type and 781 Yuan/unit for front-loading type.

4.3.7 PC Monitors

The two basic types of PCs in Chinese households are laptops and desktops. However, at the time of writing this dissertation, only national standards of energy efficiency existed for flat panel monitors used by desktop PCs. Related standards for laptops and desktops are still under development. Therefore, given the availability of required energy efficiency information, only the flat panel monitors for desktops are covered in this research.

The EEL indicator of PC monitors is stipulated in the national standard of GB 21520-2008 as *"Eff"* (in units of cd/W)[85], which is defined as follows:

[85] The unit of "cd" represents candela, which is an SI base unit of luminous intensity.

$$Eff = \frac{luminance \times screen\ area}{power\ consumed\ by\ the\ unit} \qquad (4.12)$$

Therefore, the EEG from adopting energy efficient PC monitors (namely "EEG_{PCM}") can be calculated as follows:

$$EEG_{PCM} = 1 - Eff_0/Eff_1 \qquad (4.13)$$

where "Eff_0" and "Eff_1" respectively stand for the "*Eff*" of current and efficient PC monitors.

The author's household survey in Xiamen found that the vast majority (about 91%) of the household PC monitors is within the size of 21 or 23 inches. Therefore, the PC monitors with such screen sizes were targeted in the market survey. In addition, based on a statistics of the related information on the energy labels of these monitors, it is found that the average "*Eff*" of the stock of monitors in Xiamen households is about 0.9 cd/W.

The classification of energy efficiency tiers for PC monitors in China are summarized in Table 4.15.

Table 4.15 Energy Efficiency Labelling for PC Monitors in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**		
		Tier-1	Tier-2	Tier-3
LCD Type	Eff (cd/W)	1.05	0.85	0.60

(Source: GB 21520-2008 on Energy Label, 2014)

Although the energy efficiency data of PC monitors are not available on the SUNING website, the CLASP (2013: 39), however, analyzed the price-efficiency relationship to PC monitors and concluded that "the product price is clearly driven by other factors such as screen size, brand, design, functionality, and so on, but not product efficiency." Therefore, like the LED TVs, this research assumes that no incremental cost for adopting efficient PC monitors exist in the Chinese market.

4.3.8 Electric Water Heaters

Stipulated in the national standard of GB 21519-2008, the EEL indicator of electric water heaters is expressed as the "ratio of electricity lost within 24 hours to a certain baseline (ε) (Energy Label, 2004)," which is calculated as follows:

$$Q_p = E \times 45/(\theta_m - \theta_a) \qquad (4.14)$$

$$Q = 0.015C_r + 0.8 \quad (30l < C_r \leq 100l) \qquad (4.15)$$

$$\varepsilon = Q_p/Q \qquad (4.16)$$

where *"E"* (in units of kWh) stands for the tested energy loss of a certain model of electric water heater within 24 hours; *"θ_m"* and *"θ_a"* respectively stand for the average temperature (in units of ℃) of water and ambient during the testing period; *"Q_p"* and *"Q"* respectively means the tested (after correction) and benchmark energy loss within 24 hour (in units of kWh); *"C_r"* stands for the volume of the water tank (in units of liters); *"ε"* stands for the coefficient of energy loss within 24 hours of water heaters (unitless).

Therefore, the EEG of adopting efficient electric water heaters (namely *"EEG_{EWH}"*) can be calculated as follows:

$$EEG_{EWH} = (1 - \frac{\varepsilon_1}{\varepsilon_0}) \times \frac{\varepsilon_0 \times (0.015C_r + 0.8)}{EC_{WH}/365} \qquad (4.17)$$

where *"ε_0"* and *"ε_1"* respectively stand for the coefficient of energy loss within 24 hours before and after adopting high energy efficient electric water heaters; *"EC_{WH}"* (in units of kWh/household·year) stands for the real electricity consumption of electric water heaters.

Also owing to the typical household size (2-3 occupants/household) in China, the author's Xiamen household survey found that electric water heaters almost all have a volume of 40-60 liters. Therefore, heaters with such volume were targeted in the market survey. In addition, based on the information on the energy labels of these water heaters, the Xiamen survey found that the average energy efficiency (measured in the EEL indictor of "ε") is about 0.634.

The classification of energy efficiency tiers for electric water heaters in China is summarized in Table 4.16.

Table 4.16 Energy Efficiency Labelling for Electric Water Heaters in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**				
		Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
Tank of 40-60 liter	Coefficient of Electricity-Loss within 24 hours (ε)	≤ 0.6	≤ 0.7	≤ 0.8	≤ 0.9	≤ 1.0

(Source: GB 21519-2008 on Energy Label, 2014)

Moreover, based on energy efficiency and price data on the SUNING website[86], the price of an electric water heater is primarily determined by other factors (such as control methods, new design, material adopted, etc.) rather than energy efficiency. Therefore, this research assumes that there is no incremental cost for adopting efficient electric water heaters in China.

4.3.9 Gas-Fired Water Heaters

Stipulated in the national standard GB 20665-2006, the EEL indicator of gas-fired water heaters is usually expressed as their thermal efficiency. Therefore, the EEG for adopting high energy efficient gas-fired water heaters (namely "EEG_{GWH}") can be calculated as follows:

$$EEG_{GWH} = 1 - \eta_0/\eta_1 \qquad (4.18)$$

where "η_0" and "η_1" respectively stand for the thermal efficiency of current and energy efficient gas-fired heaters.

According to the Xiamen household survey, the water output capacity of gas-fired water heaters is about 8-12 liter per minute. Therefore, the heaters with such water output capacity were targeted in the market survey. Based on the information on the energy labels of these heaters in Xiamen households, the Xiamen survey found that the average thermal efficiency of these heaters in the city is about 88%.

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[86] A total of 465 models of electric water heaters with the tank volume of 40, 50, and 60-liter were surveyed. These models were from forty-two manufacturers, including the most popular six brands in China (i.e., Media, Haier, A.O. Smith, Ariston, Macro, and Vanward).

The classification of energy efficiency tiers for gas-fired water heaters in China are summarized in Table 4.17.

Table 4.17 Energy Efficiency Labelling for Gas-Fired Water Heaters in China

Model	**Energy Efficiency Indicator**	**Energy Efficiency Tiers**		
		Tier-1	Tier-2	Tier-3
water heating only type; water output: 8-12 liter/minute	Thermal Efficiency (η)	96%	88%	84%

(Source: GB 20665-2006 on Energy Label, 2014)

The energy efficiency and price data on the SUNING website found that about 22% of the available models of gas-fired water heaters are Tier-1 products, while the remaining 78% are almost all Tier-2 products[87]. The price gaps between Tier-1 and Tier-2 products are about 485-542 Yuan/unit among different brands. In this research, the average of 514 Yuan/unit is used as the incremental cost for adopting efficiency Tier-1 gas-fired water heaters in China.

[87] A total of 112 models of gas-fired water heaters were covered in the survey, and came from nine most popular brands in China (such as Macro, Haier, Rinnai, A.O. Smith, Vanward and Vatti, etc.). Of the total 112 models, only one model is a Tier-3 product.

4.3.10 Gas-Fired Cook Stoves

The most appropriate EEL indicator for gas-fired cooking stoves is their thermal efficiency. Therefore, the EEG for adopting energy efficient stoves (namely "EEG_{GC}") can be calculated as follows:

$$EEG_{GC} = 1 - \eta_0/\eta_1 \qquad (4.19)$$

where "η_0" and "η_1" respectively stand for the thermal efficiency of current and efficient gas-fired cook stoves.

As energy efficiency labelling schemes for gas-fired cook stoves have not been implemented in China, it is impossible to get the current thermal efficiency levels of cooking stoves from the household survey. Nonetheless, some field testing research (Liu and Zhang, 2009; Zhang, 2010b) have shown that the thermal efficiency is about 50-53% for built-in type and 55-58% for desktop type of stoves.

In addition, according to CHEAA (2014), a first-ever national standard of energy efficiency for gas-fired cook stoves (GB30720) is due in 2015. In this future national standard, the Tier-1 thermal efficiency is set to be 66% for desktop type of stoves and 63% for built-in type of stoves.

To meet this new national standard of GB30720, several manufacturers in China have already developed high efficient gas cook stoves (such as FOTILE and VATTI). Based on an analysis of the prices of these efficient stoves (collected from the SUNNING website), and a relevant research conducted by the Wuppertal Institute (2013), this research assumes that the incremental cost for Tier-1 gas-fired cook stoves will be about 40% higher, and for Tier-2 stoves will be about 17% higher. The price data of gas-fired cook stoves on the SUNING website found that the current average price is about 1,690 RMB/unit for built-in type of stoves and 344 RMB/unit for desktop type of stoves[88].

4.3.11 Section Summary

Through a market survey the energy efficiency distribution of available models for various household appliances in the Chinese market were obtained. The results are summarized in Table 4.18. It needs to be noted that only the appliances models with certain capacity (namely the capacity mostly preferred by Xiamen's households) were covered in the market survey.

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[88] A total of 148 models of gas-fired cook stoves (two-burner) were covered in the market survey. These models are from the eight most popular brands in China - namely FOTILE (19 models), ROBAM (16), VATTI (26), SACON (12), MEDIA (19), VANWARD (7), MACRO (36), HAIER (13). Together they accounted for about 60% of the total sales of gas-fired cook stoves in China.

Table 4.18 Energy Efficiency Distribution of Main Household Appliances in the Chinese Market

Appliances	Distribution of Energy Efficiency[1]					Total Available Models	Capacity or Feature of Appliances
	Tier-1	Tier-2	Tier-3	Tier-4	Tier-5		
FSAC	4.1%	16.5%	79.4%	n/a	n/a	97	CC=2300W/ CC=3500W
VSAC	14.3%	37.7%	48.0%	n/a	n/a	185	CC=2300W/ CC=3500W
Refrigerators[2]	93.3%	6.7%	0%	0%	0%	105	two-door BCD type /151-230 liter volume
TVs	20.7%	26.4%	52.9%	n/a	n/a	87	LED type /32 and 42 inch
Rice Cookers	1%	62%	29%	4%	4%	344	400-600W
Top-loading Clothes Washers	16.7%	45.2%	38.1%	0%	0%	84	6-7kg
Front-loading Clothes Washers	56.9%	43.1%	0%	0%	0%	109	6-7kg
PC Monitors	43.0%	57.0%	0%	n/a	n/a	306	21-23 inch
Electric Water Heaters	48.4%	33.5%	17.2%	0.9%	0%	465	40-60 liter volume of tank
Gas-fired Water Heaters	22.2%	77.8%	0%	n/a	n/a	112	8-12 liter/minute
Gas-fired Cook Stoves	n/a	n/a	n/a	n/a	n/a	n/a	two-burner

Note: [1] As of September 2014; [2] The Tier-1 and 2 for refrigerators here respectively mean the models with electricity consumption of 0.38kWh/day and 0.48kWh/day.

(Sources: Author's statistics based on SUNING, 2014; CLASP, 2013; Author's Household Energy Use Survey in Xiamen)

Table 4.18 indicates that although the energy efficiency tiers were designed for five-levels for some appliances, the Tier 4 and 5 products of them were rarely available in the market. These include: refrigerators, rice cookers, clothes washers and electric water heaters. Further, even Tier-3 products are unavailable for certain appliances, including refrigerators, front-loading clothes washers, PC monitors and gas-fired water heaters.

Based on the analysis presented in Sections 4.3.2 through 4.3.10, the efficiency improvements potential and relevant incremental cost for selected appliances in Xiamen were summarized. The related results are shown in Tables 4.19 and 4.20.

Table 4.19 Efficiency Improvement Potential of Selected Appliances in Xiamen

Appliance	Energy Efficiency Level (EEL) Indicator	Tier-1 Efficiency	Average Efficiency of the Base-year Stock in Xiamen
FSAC	EER (W/W)	3.6	3.0
VSAC	SEER (W/W)	5.4	3.9
Refrigerators	Electricity use (kWh/24 hours)	0.38	1.2
TVs	Energy Efficient Index	3.1	1
Rice Cookers	Thermal efficiency (%)	86	80.8
Clothes Washers (Top-loading type)	Electricity use (kWh/cycle ⋅kg)	0.011	0.017
Clothes Washers (Front-loading type)	Electricity use (kWh/cycle ⋅kg)	0.11	0.19
LED PC Monitors	Eff (cd/W)	1.05	0.9
Electric Water Heaters	Coefficient (ε)	0.6	0.634
Gas Water Heaters	Thermal efficiency (%)	96	88
Cook Stoves (Built-in type)	Thermal efficiency (%)	63	51.5
Cook Stoves (Desktop type)	Thermal efficiency (%)	66	56.5

(Sources: Author's Household Energy Use Survey in Xiamen; Energy Label, 2014; Liu and Zhang, 2009; Zhang, 2010b; CHEAA, 2014)

Table 4.20 Incremental Cost of Adopting Energy Efficient Household Appliances in Xiamen

Appliance[1]	Average Incremental Cost[2]	Baseline Cost
AC	1) 607 Yuan/unit for adopting Tier-2 FSAC models; 2) 984 Yuan/unit for adopting Tier-3 VSAC models; 3) 2,303 Yuan/unit for adopting Tier-2 VSAC models; 4) 4,258 Yuan/unit for adopting Tier-1 VSAC models;	Average price of Tier-3 FSAC models
Refrigerators	255 Yuan/unit for adopting the models with electricity consumption level of about 0.38 kWh/day	Average price of the models consuming electricity 0.48 kWh/day
TVs	Insignificant	N/A
Rice Cookers	Insignificant	N/A
Front-loading Clothes Washers	781 Yuan/unit for adopting Tier-1 models	Average price of Tier-2 models
Top-loading Clothes Washers	1,188 Yuan/unit for adopting Tier-1 models	Average price of Tier-2 and 3 models
PC Monitors	Insignificant	N/A
Electric Water Heaters	Insignificant	N/A
Gas-fired Water Heaters	514 Yuan/unit for adopting Tier-1 models	Average price of Tier-2 models
Gas Cook Stoves	676 Yuan/unit for adopting future Tier-1 built-in type models; 138 Yuan/unit for adopting future Tier-1 desktop type models;	Average prices of current built-in and desktop type models

Note: [1] The specific capacity or feature of the appliances is listed in Table 4.18; [2] The incremental cost is collected as of September 2014.

(Sources: Author's statistics based on SUNING, 2014; CLASP, 2013; Liu and Zhang, 2009; Zhang, 2010b; CHEAA, 2014; Wuppertal, 2013)

4.4 Collection of Other Required Data

As shown in Table 3.3, besides the data collected from the Household Energy Use Survey and Market Survey, additional data were required for the energy-saving potential analysis. These data were obtained through literature review as well as certain estimates, including the appropriate discount rate, the life expectancy of energy-saving measures, the local actual costs of fuels, the projection of local housing and appliances stock, and the change of people's demand (or required) level of household energy services along with their income growth within the study period.

4.4.1 Selection of the Discount Rate

For cost-effective analysis, the most significant influencing factor is the applied discount rate for future cash flow. In practice, the discount rate depends on a stakeholder's expected returns. According to ACEEE (2008b: 4-7), "as each perspective portrays a specific stakeholder's view, each perspective comes with its own discount rate." There are generally three types of discount rates used for evaluating the cost-effectiveness of energy efficiency programs (ACEEE, 2008b). These are shown in Table 4.21.

Table 4.21 Discount Rates for Evaluating Energy Efficiency Programs

Perspective	Discount Rate	Calculation
Individuals	Participants' Discount Rate	uses cost of debt for an individual to finance an energy efficiency investment
Business Firms	Firms' WACC (weighted average cost of capital)	depending on the firm's credit worthiness and debt-equity structure
Whole Society	Social Discount Rate	taking into account the reduced risk of an investment that is spread across society

(Source: ACEEE, 2008b)

Among the three discount rates, the discount rates from the perspective of private individuals and business firms are usually higher than the social discount rate. Since this research primarily focuses on the benefits of reducing residential energy consumption to society as a whole over a relatively long term (i.e., the government perspective), the social discount rate is more appropriate for evaluating the economic potential of residential energy savings.

However, “the choice of an appropriate social discount rate for cost-benefit analysis… has long been a contentious issue and subject to intense debate in the economics literature (Zhuang et al., 2007: 1).” This is mainly because of the important implications of the choice of social discount rate.

> *Setting the social discount rate too high could preclude many socially desirable public projects from being undertaken, while setting it too low risks making a lot of economically inefficient investments (Zhuang et al., 2007:1).*

According to the Asian Development Bank’s report *Theory and Practice in the Choice of Social Discount Rate for Cost -benefit Analysis* (Zhuang et al., 2007), in a perfectly competitive world without market distortions, the market interest rate is the appropriate social discount rate. However, in the real world where markets are distorted, the market interest rate will not be enough to reflect marginal social opportunity. To deal with that, “economists have proposed several alternative approaches to the choice of the social discount rate in the presence of market distortions, but there has been no consensus on which is the most appropriate (Zhuang et al., 2007:1)[89]."

The ADB's research (Zhuang et al., 2007) also summarized the social discount rates utilized in some selected countries - within a broad range from 3% to 15%. It pointed out that social discount rates adopted in developed countries are relatively much lower than those in less developed countries.

In this ADB research, it was reported that the adopted social discount rate in China is usually 8%. As another reference, a social discount rate of 10% for China case was adopted in the CLASP's Policy Analysis Modeling System (PAMS)[90] (CLASP, 2005). With the above review, in this dissertation a social discount rate of 8% is adopted for the reference case analysis, while the rates of 6% and 10% are adopted for sensitivity analysis.

4.4.2 Lifetime of the Selected Energy-Saving Measures

The lifetime of household appliances varies. In the SAC's *Safety Use Lifetime of Household Appliances* (drafted in 2012 but not yet issued), the typical lifetime of various household appliances were recommended (SAC, 2012). However, the lifetime of gas-fired water heaters is not included in this document. Stipulated in the national standard GB 17905-2008 (AQSIQ and SAC, 2008), the lifetime of gas-fired water

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[89] These approaches include Social Rate of Time Preference (SRTP), Social Opportunity Cost of Capital (SOC) and Shadow Price of Capital. Each approach has its own pros and cons (Zhuang et al., 2007).

[90] This model is co-developed by the CLASP and Lawrence Berkeley National Laboratory (LBNL), which is used for policymakers to assess the benefits of EES&L programs.

heaters was recommended to be about eight years when using natural gas as the fuel. In addition, the lifetime of the residential building envelope in China is usually viewed to be about 20-25 years (Zhang, 2010a).

Based on the above review, the typical lifetime of selected energy-saving measures for the residential buildings in Xiamen is summarized in Table 4.22.

Table 4.22 Typical Lifetime of Household Appliances and the Building Envelope in China

Measures	Typical Lifetime
Air Conditioners	8-10 years
Refrigerators	12-16 years
TVs	8-10 years
Rice Cookers	10 years
Clothes Washers	8 years
PC Monitors	8-10 years
PCs	6 years
Electric Water Heaters	8 years
Gas-fired Heaters	8 years
Gas-fired cook stoves	8 years
Building Envelopes	20-25 years

(Sources: SAC, 2012; AQSIQ and SAC, 2008; Zhang, 2010a)

4.4.3 Actual Cost of Energy in Xiamen

The author's Household Energy Use Survey in Xiamen showed that the average household electricity consumption was about 2,963kWh/year. According to the currently implemented multistep electricity prices in Xiamen (shown in Table 3.10), it can be calculated that the weighted average electricity price for Xiamen's households is about 0.5078 Yuan/kWh.

The latest trading price of carbon emissions (completed in December 2013) in China is about 55.1 Yuan/ton according to the records at the China Beijing Environment Exchange (CBEEX, 2013). Given China's carbon emissions coefficient of electricity generation of about 790 grams per kWh[91] (IEA, 2012) and the average electricity transmission and distribution loss rate of about 6.31% in 2011 (CEC, 2012), it can be calculated that the carbon emissions coefficient of electricity consumption in China is about 843 grams per kWh. Accordingly, the environmental externality cost (considering only carbon emissions) of electricity consumption in China is about 0.0465 Yuan/kWh - about 9% of the retail price of electricity for Xiamen households.

The price of natural gas for Xiamen's households is 4.0 Yuan/m^3 (GFP, 2011). According to the EPA (2014), the carbon emissions factor of natural gas is about 53.06 kg/mm BTU, which is equal to about 1.9 kg carbon emissions per cubic meter natural gas use in Xiamen. Therefore, the carbon emissions cost of natural gas consumption in Xiamen is about 0.1047 Yuan/m^3 - about 2.6 % of the retail price of natural gas in the City.

In addition to the environmental externality cost of fuel use, as has been discussed in Chapter 3, the supply of both electricity and natural gas in China are subsidized by the government, which makes their retail price lower than what they

[91] The average from 2008 to 2010.

should be. It was estimated that the subsidies might be roughly about 0.54 Yuan/kWh and 1.26 Yuan/m^3 for electricity and natural gas respectively in China (Li et al., 2013).

Based on the above literature review, the actual cost of electricity and natural gas in Xiamen can be obtained, see Table 4.23.

Table 4.23 Actual Costs of Electricity and Natural Gas in Xiamen

Energy Type	Average Retail Price	Carbon Emissions Cost	Received Subsidy	Actual Cost
Electricity (Yuan/kWh)	0.5078	0.0465 (9.2%)	0.5400 (106.3%)	1.0943
Natural Gas (Yuan/m^3)	4.000	0.1047 (2.6%)	1.2600 (31.5%)	5.3647

Note: The values in the brackets show the ratio of additional cost to retail price.

(Sources: CBEEX, 2013; XMNN, 2012; IEA, 2012; CEC, 2012; GFP, 2011; EPA, 2014; Li et al., 2013)

4.4.4 Projection of Key Socioeconomic Factors

4.4.4.1 Concept of Energy Consumption

In order to project residential energy consumption (which must involve certain key socioeconomic factors, such as population, housing and appliances stock, income and so on), the concept of “energy consumption” itself needs to be carefully studied first.

According to Swisher et al. (1997), energy consumption is generally the product of two key factors:

$$EC_i = Q_i \times I_i \qquad (4.20)$$

where "EC_i" stands for the energy consumption by a certain energy service "i"; "Q_i" means the required quantity of energy service "i" (i.e., the activity level of energy service "i"); "I_i" stands for the intensity of energy consumption for the "i" energy service.

Swisher et al. (1997) further stated that the first factor (namely the "Q_i") depends on certain socioeconomic factors, while the level of energy consumption intensity (namely "I_i") depends on energy efficiency, including both technological and operational aspects[92]. As for the first factor, Swisher et al. (1997) breaks it down as follows:

$$Q_i = N_i \times P_i \times M_i \qquad (4.21)$$

where "N_i" stands of number of customers eligible for energy end-use service "i"; "P_i" stands for the penetration (total units/total customers) of end-use service "i" (i.e., the ownership of household appliances); "M_i" stands for magnitude (or extent or demand) of use of the "i" end-use service.

In the residential buildings sector, "M_i" generally indicates the frequency of use (i.e., number of showers, kg of clothes washed) or the fraction of maximum use (hours of lighting or television) for a given end-use. For cooling end-use, it may

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[92] According to Swisher et al. (1997: 29), "the intensity I_i can be reduced by changing technology to improve efficiency, without affecting the level of energy services. Energy use can also be reduced by reducing the usage of a given end-use device, thus reducing the annual energy use. If this reduction is achieved by reducing waste or unnecessary usage, for example through improved control technology, it can be considered an efficiency improvement" (but not a reduction of energy service level).

indicate the indoor-outdoor temperature difference during cooling season which have to be overcome by the space-conditioning system, or may be whatever is able to better reflect people's activity demand level of space cooling (Swisher et al., 1997).

It can be seen that, similar with the intensity concept of "I_i", the "M_i" is also a kind of intensity measurement. However, one should not be confused with these two "intensity" concepts, particularly when they are expressed in the same units. For example, for a household with a cooling load of 30 MJ/m^2 ·year (given a certain building envelope and use pattern of ACs), the energy consumption intensities for space cooling with efficiency-different ACs vary - 10 MJ/m^2 ·year for adopting ACs with average COP of 3.0, and 7.5 MJ/m^2 ·year for adopting ACs with COP of 4.0. The cooling load of 30 MJ/m^2 ·year represents the intensity of people's demand on the energy service of space cooling, while the calculated 10 and 7.5 MJ/m^2 ·year actually represents of intensity of people's energy consumption for space cooling.

In summary, according to Swisher et al. (1997), there are actually four factors central to the projection of residential energy consumption: 1) population (or housing stock[93]); 2) ownership of household appliances (or appliances stock); 3) magnitude of use (or demand level) of household energy services, and 4) energy consumption intensities for various household energy end-uses.

The fourth factor can be calculated through Equations 3.25-3.26 based on related data obtained from the Household Energy Use Survey and Market Survey. In

[93] For some certain energy end-use services (e.g., space cooling, lighting), housing floor space (m^2) is better measurement than population for energy consumption projection.

contrast, the first three factors need to be projected or analyzed within the selected time horizon (2011-2020) in this research.

4.4.4.2 Projection of Housing Stock in Xiamen

There are generally two methods to project the future housing stock. The first method was based on the data of annually added new buildings; the second is based on the data of population, average household size (i.e., number of occupants per household), and average per occupant housing floor space. One of the significant disadvantages of the first method is that a significant portion of housing units in urban China is unoccupied[94] (THUBERC, 2013). Because data on the unoccupied rate and demolition rate of residential buildings in Xiamen are not disclosed by the XBS, the first method suffers from data unavailability.

In comparison, the projection of housing stock through the second method is more credible as the impact of unoccupied and retired housing units can be avoided. Therefore, the second method is utilized in this research to project Xiamen's housing stock within the selected time horizon of 2011-2020. Actually, this method has been adopted in the CLASP's PAMS for housing stock projection (CLASP, 2005).

The projection of urban population in Xiamen is based primarily on the research of Wang (2013), which estimated Xiamen's total population growth within the period from 2010 to 2020 by applying the Grey Model GM (1, 1)[95]. However, this

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[94] According the THUBERC (2013), the share of unoccupied housing units is about 12.11% nationwide in 2005.

[95] GM (1,1) model is one of the most frequently used Grey Forecasting models. This model is a time series forecasting model, encompassing a group of differential equations adapted for parameter variance, rather than a first-order differential equation (Li and Xie, 2014).

total population includes both urban and rural population in Xiamen. Therefore, the rural population of Xiamen should be removed from the total population projected by Wang (2013). According to the XBS (2003-2011), the rural population of Xiamen has been very stable during the past decade - about 0.36 million. By subtracting this stable rural population from the projected total population by Wang (2013), the urban population of Xiamen within the time period of 2011-2020 was obtained.

According to the statistical data of the XBS (2003-2011), the average per occupant housing floor space and household size (namely occupants per household) in Xiamen were respectively about 32.5m^2/capita and 2.39 persons/household in 2011. In addition, the historical data showed that there was an increasing trend for the average housing floor space per occupant (with an annual rate of about 1%), and a decreasing trend of average household size (with an annual rate of about 1.4%). This research assumes that such trends and changing rates will remain in Xiamen during the period of 2011 to 2020.

In summary, based on the collected data and related assumptions, the housing stock in urban Xiamen from 2011 to 2020 could be estimated, as indicated in Table 4.24.

Table 4.24 Projection of the Households and Housing Stock in Xiamen

Year	Urban Population (thousand)	Housing Floor Space (m^2/person)	Household Size (persons/ household)	Households (thousand)	Housing Stock (thousand m^2)
2011	3,247	32.5	2.39	1,358.4	10,5514.5
2012	3,312	32.8	2.36	1,405.5	10,8716.4
2013	3,379	33.2	2.32	1,454.2	11,2024.8
2014	3,448	33.5	2.29	1,504.9	11,5445.5
2015	3,518	33.8	2.26	1,557.4	11,8980.8
2016	3,590	34.2	2.23	1,611.9	12,2633.4
2017	3,664	34.5	2.20	1,668.4	12,6405.8
2018	3,740	34.8	2.17	1,727.1	13,0314.6
2019	3,818	35.2	2.14	1,788.0	13,4348.7
2020	3,897	35.5	2.11	1,851.1	13,8518.0

(Sources: Wang, 2013; XBS, 2003-2011)

4.4.4.3 Projection of Appliances Stock in Xiamen

Besides population growth (i.e., the factor "N_i"), the residential energy consumption might be significantly influenced by household income growth (i.e., the factors "P_i" and "M_i"). Given China's expected robust economic growth in the near future, the household income in Xiamen might keep growing. Generally, the energy consumption of a household will grow along with the increase of its household income (particularly in less developed countries). This is due mainly to three factors: 1) more household appliances are adopted (namely, the growing ownership of appliances); 2) larger-size or larger-capacity appliances are adopted; and 3) appliances are used longer or more often. The last two factors are actually about the demand level change of diverse household energy services, and will be discussed in Section 4.4.4.4. This section discusses the ownership of appliances in Xiamen's households.

Based on the XBS's statistical data during the past decade, Table 4.25 shows the ownership changes of main household appliances in Xiamen.

Table 4.25 Ownership of Main Household Appliances in Urban Xiamen

Year	**Appliances** (units/100 households)						
	TVs	Refrigerators	Clothes Washers	PCs	ACs	Water Heaters	Microwave Ovens
2003	147.0	102.5	98.0	62.5	149.5	95.0	74.5
2004	148.5	102.5	93.5	58.0	166.0	101.0	84.0
2005	151.0	102.5	95.0	66.5	187.0	102.0	86.0
2006	153.5	103.5	97.5	79.5	197.5	109.0	88.0
2007	158.5	105.5	101.5	88.0	223.5	101.5	89.5
2008	136.7	102.3	95.7	94.3	207.7	95.7	85.3
2009	150.0	107.0	97.0	107.0	223.0	114.0	90.0
2010	151.0	108.0	99.0	117.0	237.0	114.0	91.0
2011	135.2	107.2	94.2	124.0	233.0	110.2	84.4
2012	141.2	109.9	96.6	131.3	243.7	110.1	85.1

(Sources: XBS, 2003-2011, 2012a, 2013)

From Table 4.24, it can be seen that the penetration of TVs, refrigerators, clothes washers, water heaters and microwave ovens in Xiamen's households has remained stable during the past decade. In contrast, the penetration of PCs and ACs experienced a fast increase in the early years of the past decade. Nonetheless, the recent trend of AC penetration (e.g., 2010-2012) shows that it is approaching saturation in Xiamen's households (especially considering the vast majority of two-bedroom housing in the City). As for PCs, the trend shows that it may increase in the coming years. As mentioned before, only the PC monitors for desktops are covered in the potential analysis, and they account for only about 1% of the household electricity consumption in Xiamen according to the household survey. Therefore, given its small influence on REC[96], in order to simplify the calculation the ownership of PCs is set to be 1.46 per household (see Table 4.4) in this research during the study period. The ownership of rice cookers and gas-stoves are not included in the XBS's statistics. According to the author's Household Energy Use Survey in Xiamen, for both of these appliances the ownership stands at one unit per household.

In summary, in this research, the ownership of main household appliances in Xiamen is considered as unchanged from the base year. Accordingly, the stocks of these appliances in 2020 could be calculated by multiplying the surveyed 2011 ownership of them and the projected Xiamen households in Table 4.24.

It is worth noting that if some new appliances (namely those in their very beginning stage of market penetration, such as the ACs in Xiamen during 2003-2007)

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[96] In fact, as this research includes a scenario analysis of increasing household income on REC (see Section 4.4.4.4), the impact of potential increase in ownership of PCs on REC could be to some extent reflected in the results of that scenario analysis.

are involved, the future ownership of them needs to be credibly estimated. In these cases, the Bass adoption model can be applied (NREL, 2012). Developed from Rogers' pioneering study of "Diffusion of Innovations" (Rogers, 1995), the Bass adoption model is defined in a differential equation that involves two coefficients representing the effectiveness of communication on the adoption of the new appliances, namely external influence (e.g., mass-media) and internal influence (e.g., interpersonal communication) (Bass, 1969).

4.4.4.4 Projection of People's Demand Level of Household Energy Services in Xiamen

The research on the influences of household income growth on the increase of people's demand levels of household energy services has rarely been seen in existing research literature, and the related analytical approaches are still contested among researchers (e.g., see IRGC, 2013; ACEEE, 2012; Ouyang et al., 2010). Therefore, it is challenging to establish a reliable relationship between them.

According to Swisher et al. (1997), there are generally two kinds of methods for measuring such influences. The first kind is the *Econometric Models*, which tries to regress the "demand levels of energy services" to some key economic factors. A popular form of the regression models is based on the Cobb-Douglas Production Function in microeconomics, expressed as follows:

$$E = a \times Y^{b1} \times P^{b2} \qquad (4.22)$$

where "*E*" stands of the demand level of energy services; "*Y*" stands for household income; "*P*" stands for energy price; "*a*", "*b1*" and "*b2*" stand for coefficients.

This method has the significant advantage of requiring fewer data, and also easier data collection. The disadvantage of this method is its aggregated nature. In other words, all household energy services have to be combined as a whole to be measured, rather than being broken down as a various end-uses (e.g., TVs, clothes washers, etc.).

The second method is the disaggregated *End-use Model*, which breaks down the household services into various end-uses, and discusses them separately. The disadvantage of this method is that it requires a large number of detailed data, which are often very difficult to obtain. Sometimes, the data are unavailable at all, particularly in developing countries.

In this research, mainly owing to data availability, a combination of the two methods is applied to analyze the change of people's demand levels of household energy services along with the increase of their income growth. First, a qualitative analysis of the change of people's demand level of energy service for each end-use is implemented using Swisher et al. (1997) concept of *End-use Model*. Then, a quantitative analysis based on Swisher et al. (1997) *Econometric Model* is made to project the future trend of people's demand level of aggregated electricity services in Xiamen's households.

As mentioned before, the household energy services in Xiamen can be divided into five end-use groups: space cooling, lighting, water heating, plug-in appliances[97] and cooking. In order to discuss the demand levels of energy services for these end-

[97] There are a variety of plug-in appliances, however, a further breakdown is difficult given the limited available data in China. In this research, all plug-in appliances are considered as a whole for the discussion of people's demand level of energy services.

uses, an appropriate “measurement unit” is identified for each energy end-use first. The selected “measurement unit” should be able to reflect the nature of each end-use. In this research, the “measurement unit” for cooking and water heating are both “MJ/person·year;” for plug-in appliances it is “MJ/household·year;” for lighting the unit is “MJ/m^2;” for space cooling, both “MJ/m^2”and “MJ/household·year” are suitable (however, considering the operation mode of ACs in Chinese households, the unit of “MJ/household·year” is preferred in this research).

Among the five household energy end-use groups, people’s demand levels of energy services for the three end-use groups, plug-in appliances, ACs and water heating, might grow along with their income increase (e.g., people using plug-in appliances and ACs longer, taking more showers or starting to use hot water for other purpose than current showering only, lowering the indoor temperature setting for space cooling, etc.). In contrast, given the current economic development level in Xiamen, people’s demand levels of energy services for lighting and cooking might not be influenced by higher household income. It was found that people usually do not cook more at home when their income increases (THUBERC, 2013).

According to author’s Household Energy Use Survey in Xiamen, most of the electricity (about 91%) in Xiamen’s households is consumed by ACs, plug-in appliances and electric water heaters. Thus, it can be generally concluded that the household income increase in Xiamen could cause the growth of required level of electricity services in the city. Based on Equation 4.22, Xiamen’s “residential electricity consumption intensity” (in units of kWh/capita·year) and per capita GDP (in units of Yuan/capita) are respectively utilized in this research as the agents of people's demand level of household electricity services and household income in the city. The historical data of them can be obtained from the XBS statistics.

According to the XBS (2014, 2013, 2012a, 2003-2011), the residential electricity consumption intensity (kWh/capita ·year) and GDP (Yuan /capita) in Xiamen are shown in Figure 4.11[98].

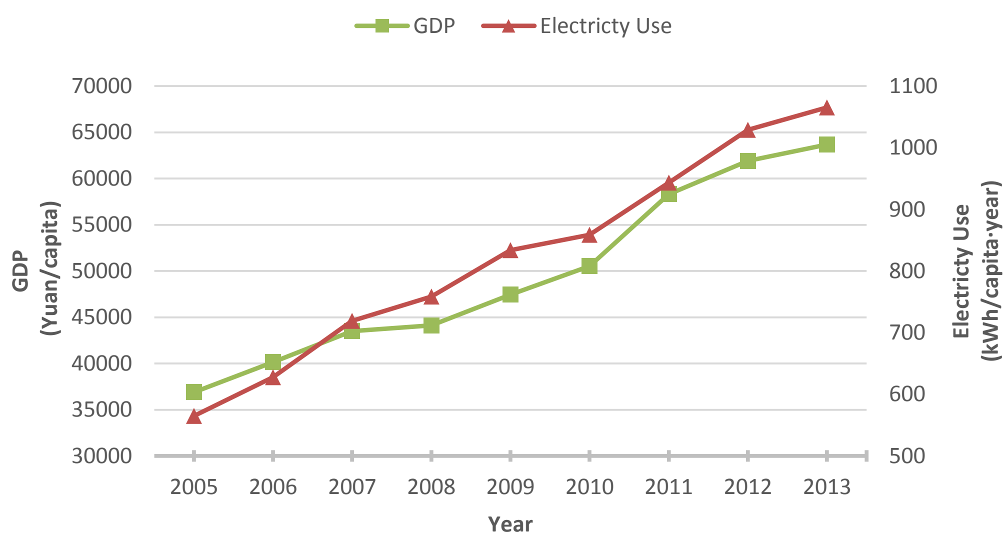

Figure 4.11 Residential Electricity Use and GDP in Xiamen 2005-2013

(Sources: XBS, 2014, 2013, 2012a, 2003-2011)

The household electricity market in China is regulated. As a consequence, the electricity price for households is usually fixed, only being adjusted every a few years. In the case of Xiamen, the electricity price for household use was fixed at about

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[98] The GDP of Xiamen is based on a 2005 constant price.

0.4543 Yuan/kWh from 2004 to 2012, and has been adjusted to be about 0.5078 Yuan/kWh since 2012 (XMNN, 2012)[99].

With the obtained Xiamen data of "E", "Y" and "P" during the period of 2005-2013, the econometric Equation 4.22 for the Xiamen case is able to be achieved. The regression equation is expressed as follows:

$$Ln\ (E) = 1.1086\ Ln\ (Y) - 0.1605\ Ln(P) - 5.4 \qquad (4.23)$$

Regression Statistics	
Multiple R	0.982601779
R Square	0.965506256
Adjusted R Square	0.954008341
Standard Error	0.046291293
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.359885731	0.179942866	83.97229199	4.10413E-05
Residual	6	0.012857303	0.002142884		
Total	8	0.372743034			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
a	-5.4002018	1.313001542	-4.1128678	0.006266163
b2	-0.1605318	0.514336287	-0.3121145	0.765515384
b1	1.1085777	0.098369203	11.2695613	2.91882E-05

[99] Xiamen has enforced multistep electricity pricing since 2004. The electricity price presented here is a weighted average based on the surveyed average annual household electricity consumption in Xiamen - about 2,964 kWh/household year.

The "*R square*" for the regression is high (about 0.9655); the "*Significance F*" is almost zero - meaning an extremely high confidence level of the regression; the "*p-values*" for the coefficients of "*a*" and "*b1*" are both almost zero. However, the "*p-value*" for "*b2*" (about 0.7655) is much above the significant level of 0.05, implying that the involvement of "electricity price" as an independent variable in the regression is not necessary. The larger "*p-value*" for the "*b2*" reflects the reality of regulated electricity market in China.

By removing the variable of "*P*" from the regression, Equation 4.22 can be simplified accordingly as follows:

$$E = a \times Y^{b1} \qquad (4.24)$$

According to the historical data presented in Figure 4.11, Equation 4.24 can be regressed as:

$$Ln\ (E) = 1.0928\ Ln\ (Y) - 5.1 \qquad (4.25)$$

Regression Statistics	
Multiple R	0.982316761
R Square	0.964946218
Adjusted R Square	0.959938535
Standard Error	0.043203923
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.359677	0.359677	192.6931	2.38E-06
Residual	7	0.013066	0.001867		
Total	8	0.372743			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
a	-5.104989313	0.849947	-6.00624	0.000539
b1	1.092780073	0.078723	13.8814	2.38E-06

From the regression statistics, it can be seen that the "*R square*" is still very high (about 0.9649), while the "*p-values*" for "*a*" and "*b1*" are both almost zero.

At the end of 2014, the Xiamen Development and Reform Commission (XDRC) (2014) issued the report of *Strategic Thinking of Xiamen's Socio-Economic Development during the 13th FYP (2016-2020)*. In this report, the XDRC estimated that Xiamen's GDP would keep an annual increase rate of about 8.5% from 2016-2020. Based on this estimate of XDRC and the projected Xiamen population during 2016-2020 (see Table 4.23), the trend of "per capita GDP" in Xiamen from 2016 to2020 was obtained.

Accordingly, the demand level of electricity service in Xiamen households from 2014 to 2020 was projected based on Equation 4.25[100], as shown in Table 4.26. As a reference, the projection from Equation 4.23 is also shown in Table 4.26.

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100 At the time of writing this dissertation, the data of Xiamen's "per capita GDP" and "residential electricity use intensity" before 2013 has been published by the XBS (2014, 2013, 2012a) (see Figure 4.11).

Table 4.26 Projected Residential Electricity Intensity in Xiamen 2014-2020

Year	**Residential Electricity Intensity** (kWh/capita ·year)	
	Regression Equation 4.23	Regression Equation 4.25
2014	1,103	1,115
2015	1,145	1,157
2016	1,189	1,201
2017	1,233	1,245
2018	1,280	1,292
2019	1,328	1,339
2020	1,378	1,389

(Sources: Author's calculation; Swisher et al., 1997; XBS, 2014, 2003-2011; XDRC, 2014; XMNN, 2012; Wang, 2013)

Table 4.26 shows that the projection results from the two regression equations are very close (with the gap about 0.8%-1%). According to the results, it can be reliably estimated that people's demand on electricity services in Xiamen on average may increase by **3.73%** annually from 2014 to 2020. The XBS statistical data (2014, 2013, 2012a) showed that an average rate of increase was **4.09%** during 2011-2014.

These annual increase rates are the values of $\gamma_{(i,j)}$ in Equation 3.26. As discussed before, the increasing demand level of electricity services in Xiamen households is mainly reflected on three end-uses, namely, plug-in appliances, ACs and water heating. It is worth noting that the increase rates may be different among the three end-uses. However, restricted by data availability, a further breakdown of the aggregated increase rate among the end-uses is hardly possible (which can be a future research topic for residential energy consumption projection).

As a reference, Table 4.27 presents a comparison of residential energy consumption intensities by end-uses between Xiamen and Hong Kong. Hong Kong lies in the same HSWW (hot summer and warm winter) climate zone as Xiamen, but has a much higher level of economic development. Currently, the per capita GDP (PPP) in Xiamen is only about half of that of Hong Kong (World Bank, 2014).

Table 4.27 Comparison of Residential Energy Intensities by End Uses in Xiamen and Hong Kong

Energy End Use	**Units of Intensity**	**Xiamen** (2011)	**Hong Kong**[1]
Cooking	MJ/person·year	3,564.4	1,614.2
Plug-in Appliances	MJ/household·year	4,990.2	7,039.2
Water Heating	MJ/person·year	1,158.2	1,533.7
Space Cooling	MJ/ household·year	2,667.7	4,956.2

Note: [1] The data of Hong Kong is the average in 2005-2011.

(Sources: EMSD, 2007-2013; Author's Household Energy Use Survey in Xiamen)

From Table 4.27, it can be seen that there are significant gaps of energy consumption intensity for plug-in appliances, water heating and space cooling between Xiamen and Hong Kong. In contrast, the energy use intensity for cooking in Hong Kong is much lower than that in Xiamen. The main reason may lie in that the people in Hong Kong eat out much more frequently than their counterparts in Xiamen because of their busier lifestyle. On one hand, this fact clearly shows that cooking energy intensity does not positively correlate to household income level; on the other hand, it shows that there may have some energy consumption transfer among sectors (e.g., from residential sector to commercial sector) along with people's income growth.

4.5 Chapter Summary

In this Chapter, data collection for analyzing the residential energy-saving potential in the city of Xiamen was introduced. In addition to the policy review presented in Chapter 2, there are three other data collection methods involved: 1) a household energy use survey; 2) a market survey; and 3) literature review. Although these methods are introduced through a case study of Xiamen, they are general methods and can be applied to other southern Chinese cities as well.

As shown in Chapter 3, the primary step for energy-saving potential analysis is knowing the status quo of residential energy consumption patterns in the case study city, including energy efficiency levels of various household energy end-uses, shares of different types of appliances, as well as people's use patterns of the appliances. A well-designed Household Energy Use Survey is able to provide reliable enough data to map the residential energy consumption patterns for policy analysis.

Different from the Household Energy Use Survey, which exclusively focuses on the existing stock of household energy use measures, the Market Survey primarily targets the available options for advanced technical measures for local consumers. In the Market Survey, the appropriate "Energy Efficiency Level (EEL)" indicator for each technical measure needs to be identified first based on local disclosure context of related information (i.e., China's EES&L schemes for appliances in this research). The "efficiency-price relationship" of available measures can then be surveyed based on market information. With such relationships, the incremental cost of adopting efficient measures can be observed, which are critical for the economic and achievable potential analyses.

Besides the data obtained from the Household Energy Use Survey and Market Survey, there are still a number of additional data required for the analysis of residential energy-saving potential. Generally, these data can be obtained through reviewing related research literature or reasonable estimates based on certain calculations, including an appropriate social discount rate, the typical life expectancy of selected technical measures, the actual cost of local fuels, and the projection of certain socioeconomic factors which are closely in relation to household energy use (such as population, housing stock, ownership of appliances, household income, and people's demand level of household energy services, etc.).

Based on all the obtained data for the Xiamen case, the various types of residential energy-saving potential in the city of Xiamen can be comprehensively analyzed, including technical potential, economic potential and achievable potential (both maximum and possible). Results of the potential analysis for the Xiamen case are presented and discussed in Chapter 5.

Chapter 5

ANALYSIS OF RESIDENTIAL ENERGY-SAVING POTENTIAL IN XIAMEN

This chapter analyzes energy-saving potential (i.e., technical, economic, maximum achievable and possible achievable) in Xiamen's urban residential buildings. It comprises of five sections. The first two sections analyze, respectively, the technical and economic potential in Xiamen. These are static potential analysis, and could provide policymakers with a general picture of the potential scale of energy savings in the city's residential buildings sector. Sections 3 and 4 respectively analyze the "maximum achievable potential (MAP)" and "possible achievable potential (PAP)" of residential energy savings in Xiamen. These analyses are based on a projection model of residential energy consumption (REC), namely Equations 3.14-3.27 that were structured in Chapter 3. The achievable potential analyses are dynamic primarily because they take into account the realistic gradual ramping-up adoption process of advanced technical measures and individuals' adoption-decision making on them within a certain time horizon. The analysis of achievable potential can be used as a policy analysis tool to quantitatively evaluate the real-world impact of different policy interventions on residential energy savings. The last section is a Chapter summary and highlights the main research findings from the four types of residential energy-saving potential analysis in Xiamen.

5.1 Analysis of Technical Potential

As shown in Chapter 3, the calculation of technical potential depends primarily on two types of factors, namely the current energy consumption levels of household energy use equipment and their energy efficiency improvements potential. The related data were summarized in Figure 4.6 and Table 4.19 of Chapter 4. Based on the collected data, the technical potential of electricity savings and natural gas savings in Xiamen's residential buildings were estimated. The results are shown in Sections 5.1.1 and 5.1.2.

5.1.1 Potential of Electricity Savings

Although the general calculation principles for technical potential can be easily expressed (as shown in Equations 3.7-3.9), the specific calculation process (particularly for electricity savings) often becomes complicated for two reasons. First, energy efficiency levels among different types of appliances can vary significantly (e.g., fixed-speed and variable-speed type for air conditioners, CRT, CCFL, PDP and LED type for TVs, front-loading and top-loading type for clothes washers), and, therefore, the technical potential calculation must consider the possible "replacement effects" of different types of appliances. Second, for energy savings from space cooling, the measures of building envelope retrofitting and the measure of adopting energy efficient ACs are completely interlinked, and need to be considered in an integrated manner[101].

[101] Improved building envelopes (e.g., roof and wall insulation, low-E windows, etc.) could result in reduced cooling loads. Accordingly, the energy-saving effects of adopting efficient air conditioners must first take into account the changed cooling loads caused by envelope retrofitting. In calculation, these interlinked effects are often expressed by the concept of *Interaction Factor* (ACEEE, 2008c).

To better present the intermediate process data (which are also informative to policymakers) in a clear and brief way, the calculation process of technical potential is organized by means of a matrix, shown below.

<u>Step 1:</u> Forming the *Electricity Consumption Intensities Distribution (ECID)* Matrix:

$$M\ (ECID) = \left[\frac{E_i}{E_{TAL}}\right] = \left[\frac{E_{SC}}{E_{TAL}}, \frac{E_{RE}}{E_{TAL}}, \frac{E_{RC}}{E_{TAL}}, \frac{E_{TV}}{E_{TAL}}, \frac{E_{PCM}}{E_{TAL}}, \frac{E_{WM}}{E_{TAL}}, \frac{E_{EWH}}{E_{TAL}}\right]$$

$$= [25.1\%, \quad 15.7\%, \quad 7.5\%, \quad 7.2\%, \quad 1.0\%, \quad 2.5\%, \quad 18.9\%]$$

where "E_{TAL}" stands for the total electricity consumption intensity (in units of MJ/m² ·year); the "E_i" stands for the electricity consumption intensity of a certain type of appliance "i". In the Xiamen case study, there are seven appliances involved[102] - "E_{SC}", "E_{RE}", "E_{RC}", "E_{TV},", "E_{PCM}", "E_{WM}" and "E_{EWH}" respectively stand for the electricity consumption intensities of air conditioners, refrigerators, rice cookers, TVs, PC monitors[103], clothes washers, and electric water heaters.

The values of these energy consumption intensities for the Xiamen case are obtained from Figure 4.6 in Chapter 4.

[102] It must be noted that the sum of the energy consumption intensities of these seven appliances is not equal to the "E_{TAL}", as some other plug-in appliances (e.g., microwave ovens, DVD players) whose efficiency is difficult to improve at current stage are not considered for the calculation of technical potential in this research.

[103] The electricity consumption intensity of PC monitors is about 22% of that of PCs according to the author's Household Energy Use Survey in Xiamen.

The size of the *ECID* Matrix is $1\times k$, where k represents number of selected appliances. It can be seen that the elements in this matrix actually represent the electricity consumption shares of various appliances.

Step 2: Forming the *Adjusted ECID* Matrix (namely the *ECID* Matrix after completing the retrofits of a building envelope):

$$M\ (Adjusted\ ECID) = \left[\frac{E_i'}{E_{TAL}'}\right] = \left[\frac{E_{SC}'}{E_{TAL}'}, \frac{E_{RE}}{E_{TAL}}, \frac{E_{RC}}{E_{TAL}}, \frac{E_{TV}}{E_{TAL}}, \frac{E_{PCM}}{E_{TAL}}, \frac{E_{WM}}{E_{TAL}}, \frac{E_{EWH}}{E_{TAL}}\right]$$

$$= [16.5\%,\quad 17.4\%,\quad 8.3\%,\quad 8.0\%,\quad 1.1\%,\quad 2.7\%,\quad 21.1\%]$$

where "E_{TAL}'" and "E_{SC}'" respectively stand for the total electricity consumption intensity and that of space cooling after retrofitting a building envelope. Therefore, the elements in this matrix actually represent the electricity consumption shares of various appliances in buildings whose envelopes have been retrofitted.

As discussed in Section 4.3.1 of Chapter 4, the cooling load in Xiamen's residential buildings could be reduced by about 40.8% by retrofitting the building envelope. Therefore, given the electricity consumption intensity of space cooling (namely 28.5 MJ/m^2·year) in Xiamen, both of the "E_{TAL}'" and "E_{SC}'" will be 11.6 MJ/m^2·year less than the "E_{TAL}" and "E_{SC}" respectively.

Step 3: Forming the *Selected Technical Measure (STM)* Matrix:

$$M\ (STM) = \begin{bmatrix} FSAC & VSAC & 0 \\ RE & 0 & 0 \\ RC & 0 & 0 \\ CRT + PDP^{104} & CCFL & LED \\ PCM & 0 & 0 \\ FRONT & TOP & 0 \\ EWH & 0 & 0 \end{bmatrix}$$

where *FSAC* (fixed-speed air conditioner), *VSAC* (variable-speed air conditioners), *RE* (refrigerator), *RC* (rice cooker), *CRT* (CRT TV), *PDP* (PDP TV), *CCFL* (CCFL TV), *LED* (LED TV), *PCM* (PC Monitor), *FRONT* (front-loading clothes washers), *TOP* (top-loading clothes washers), and *EWH* (electric water heater) stand for specific technical measures selected for technical potential analysis. This *STM* Matrix is structured for the Xiamen case based on the findings on appliances stocks from the Household Energy Use Survey in the city.

In this matrix, each row represents a certain kind of appliance, while the columns in a row represent different types of that appliance. Accordingly, the size of the matrix is determined by two factors: 1) the total *kinds* of selected appliances for rows (which are seven in the Xiamen case); and 2) the maximum number of types of selected appliances for columns (which are three in the Xiamen case). A null value is applied for non-existing elements.

<u>Step 4:</u> Forming the Matrix of *Electricity Consumption Distribution within Types of Appliances (ECDTA)* according to the structure of *STM* Matrix:

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104 As there is no "Energy Efficiency Index (EEI)" standard for CRT TVs and the calculation method of "EEI" for PDP TVs differs from that of LCD TVs (i.e., CCFL and LED TVs), in this research, these two kinds of TVs are combined together as one for the calculation of technical potential.

$$M\ (ECDTA) = \begin{bmatrix} 0.902 & 0.098 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0.187 & 0.664 & 0.149 \\ 1 & 0 & 0 \\ 0.774 & 0.226 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

In this matrix, every row shows the electricity consumption shares of different types of a selected appliance. For example, as shown in the first row, FSACs account for 90.2% of electricity consumption by air conditions in Xiamen's households, while VSACs account for the rest 9.8%. These shares are calculated based on the author's Household Energy Use Survey data - namely the "stock shares" (see Table 4.4) and current "average energy efficiency levels" (see Table 4.19) of different types of the selected appliances.

Step 5: Forming the Matrix of *Current Energy Efficiency Levels of Appliances (CEELA)* according to the structure of *STM* Matrix:

$$M\ (CEELA) = \begin{bmatrix} 3 & 3.9 & 0 \\ 1.2 & 0 & 0 \\ 0.808 & 0 & 0 \\ 0.84^{105} & 0.84 & 1.47 \\ 0.9 & 0 & 0 \\ 0.19 & 0.017 & 0 \\ 0.634 & 0 & 0 \end{bmatrix}$$

In this matrix, the values of the current energy efficiency levels of selected appliances are obtained from Table 4.19. It must be noted that the energy efficiency level indicators differ among appliances.

<u>Step 6:</u> Forming the Matrix of *Highest Energy Efficiency Levels of Appliances (HEELA)* according to the structure of *STM* Matrix:

$$M\ (HEELA) = \begin{bmatrix} 3.6 & 5.4 & 0 \\ 0.38 & 0 & 0 \\ 0.86 & 0 & 0 \\ 3.1 & 3.1 & 3.1 \\ 1.05 & 0 & 0 \\ 0.11 & 0.011 & 0 \\ 0.60 & 0 & 0 \end{bmatrix}$$

In this matrix, the values of the highest energy efficiency levels of selected appliances are obtained from Table 4.19. In the fourth row, the energy efficiency levels for the three columns are all give a number of 3.1 (i.e., Energy Efficiency Index

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[105] According to the author's Household Energy Use Survey in Xiamen, the weighted average on-mode wattage of CRT and PDP TVs in Xiamen is about 144W/unit, which is almost equal to the average on-mode wattage of CCFL TVs (143W/unit). Therefore, to simplify the calculation, it is assumed in this research that the combined stock of CRT and PDP TVs holds the same average "EEI" with the stock of CCFL TVs.

=3.1 for all the three types of TVs) because only LED TVs are currently available for sale in the Chinese market.

<u>Step 7:</u> Forming the Matrix of *Energy Efficiency Gap of Appliances (EEGA)*:

$$M\ (EEGA) = \begin{bmatrix} 0.167 & 0.278 & 0 \\ 0.683 & 0 & 0 \\ 0.060 & 0 & 0 \\ 0.642 & 0.642 & 0.425 \\ 0.143 & 0 & 0 \\ 0.353 & 0.421 & 0 \\ 0.034 & 0 & 0 \end{bmatrix}$$

In this matrix, the energy efficiency gap (EEG) values of selected appliances are calculated based on the *CEELA* Matrix and *HEELA* Matrix, as well as the EEG calculation methods shown in Section 4.3 of Chapter 4.

Therefore, the value of "$EEGA_{(i,j)}$" represents the maximum reduction potential of current electricity consumption by the "*j*" type of "*i*" kind appliance (expressed in the form of a reduction percentage from the current electricity consumption level). For example, the value of "0.167" in row 1 and column 1 means that adopting the most efficient FSACs could reduce the current electricity consumption intensity of FSACs in Xiamen (after building envelope retrofits) by about 16.7%.

<u>Step 8:</u> Forming the Matrix of *Weighted EEGA*:

$$M\ (Weighted\ EEGA) = \begin{bmatrix} 0.151 & 0.027 & 0 \\ 0.683 & 0 & 0 \\ 0.060 & 0 & 0 \\ 0.120 & 0.426 & 0.063 \\ 0.143 & 0 & 0 \\ 0.273 & 0.095 & 0 \\ 0.034 & 0 & 0 \end{bmatrix}$$

In this matrix, the element of "*Weighted* $EEGA_{(i.\ j)}$" is calculated through multiplying the "$EEGA_{(i,\ ,j)}$" by the "$ECDTA_{(i,\ ,j)}$". After this calculation, the "*weighted* $EEGA_{(i,\ .j)}$" represents the maximum reduction potential of current electricity consumption by the "*i*" kind appliance which is caused by the "*j*" type of this appliance (expressed in the form of a reduction percentage from the current electricity consumption level). For example, the value of "0.151" in row 1 and column 1 means that adopting the most efficient FSACs could reduce the current electricity consumption of air conditioners in Xiamen (after building envelope retrofits) by about 15.1%.

<u>Step 9:</u> Forming the Matrix of *Accumulated EEGA* based on the Matrix of *Weighted EEGA*:

$$M\ (Accumulated\ EEGA) = \begin{bmatrix} 0.178 \\ 0.683 \\ 0.060 \\ 0.609 \\ 0.143 \\ 0.368 \\ 0.034 \end{bmatrix}$$

In this matrix, the element of "*Accumulated* $EEGA_{(i,.j)}$" is calculated through "$\sum_j Weighted\ EEGA_{(i,j)}$". After this calculation, the "*Accumulated* $EEGA_{(i,\ .j)}$"

represents the maximum reduction potential of current electricity consumption by the "i" kind appliance (expressed in the form of a reduction percentage from the current electricity consumption level). For example, the value of "0.178" in row 1 and column 1 means that adopting most efficient FSACs and VSACs (without considering the replacement effects between the two types of air conditioners) could help to reduce the current electricity consumption by air conditioners in Xiamen (after building envelope retrofits) by about 17.8%.

From this matrix, it can be observed that the current electricity consumption of air conditioners, refrigerators, rice cookers, TVs, PC monitors, clothes washers and electric water heaters in Xiamen's households could be reduced by about 17.8%, 68.3%, 6.0%, 58.2%, 14.3%, 36.8%, and 3.4% respectively.

<u>Step 10:</u> Calculating the technical potential of electricity savings after building retrofits ("$\sum ES_{ij}$") as follows:

$$\sum ES_{ij} = M(Accumulated\ EEGA) \times M\ (Adjusted\ ECID)$$

$$= \begin{bmatrix} 0.178 \\ 0.683 \\ 0.060 \\ 0.609 \\ 0.143 \\ 0.368 \\ 0.034 \end{bmatrix} [16.5\%, \quad 17.4\%, \quad 8.3\%, \quad 8.0\%, \quad 1.1\%, \quad 2.7\%, \quad 21.1\%] =$$

$$= 2.94\% + 11.88\% + 0.50\% + 4.87\% + 0.16\% + 0.99\% + 0.72\% = 22.1\%$$

It can be seen that the electricity-saving potential in Xiamen's households from adopting the most efficient air conditioners, refrigerators, rice cookers, TVs, PC monitors, clothes washers and electric water heaters are about 2.94%, 11.88%, 0.5%, 4.87%, 0.16%, 0.99% and 0.72% respectively (using the 2011electricty consumption level after building envelope retrofits as the baseline, namely the "E'_{TAL}").

Step 11: Calculating the total technical potential of electricity savings (in the form of a reduction percentage from the 2011 baseline) as follows:

$$\frac{\left[(E'_{TAL} \times \sum ES_{ij}) + (E_{TAL} - E'_{TAL})\right]}{E_{TAL}}$$

$$= [(102.1 \times 22.1\%) + (113.7 - 102.1))]/113.7 = 34.14/113.7 = 30.0\%$$

Based on the above calculation, Table 5.1 summarizes the technical potential of electricity savings in Xiamen's residential buildings.

Table 5.1 Technical Potential of Electricity Savings in Xiamen's Residential Buildings

Measures	Electricity Savings (MJ/m^2·year)	Baseline Energy Consumption (MJ/m^2·year)
Building Envelope Retrofitting[1]	11.63	28.5
Tier-1 ACs	3.00 [2]	
High-Efficiency Refrigerators[3]	12.13	17.8
Tier-1 Rice Cookers	0.51	8.5
Tier-1 TVs	4.97	8.2
Tier-1 PC Monitors	0.16	1.0
Tier-1 Clothes Washers	1.01	2.8
Tier-1 Electric Water Heaters	0.73	21.5
Total	34.14	113.7

Note: [1] The envelope retrofitting measures include roof insulation and adoption of high-performance windows (see details in Section 4.3.1 of Chapter 4); [2] Energy savings from ACs are after the building envelope retrofits; [3] The High-Efficiency refrigerators means the ones whose electricity use is about 0.38 kWh/day.

(Source: Author's calculation)

From the above calculation, it can be seen that the technical potential of electricity savings in Xiamen's residential buildings could be about 34.14 MJ/m^2·year**,** meaning a reduction percentage of about **30.0%** from the 2011 baseline level (i.e., 113.7 MJ/m^2·year). It is worth noting that adopting energy efficient refrigerators, air conditioners and TVs is extremely important, as they together could contribute to a total electricity-saving potential of about 20.1 MJ/m^2·year - meaning a reduction percentage of about 17.7% from the 2011 baseline level.

It must be noted, however, that the "replacement effects" among different types of certain appliances are not considered in the above calculation. Such replacement could have a significant impact on the scale of technical potential given the distinct difference in efficiency among the different types of certain appliances.

According to the Market Survey, there are currently two kinds of possible replacements for electricity consumption in Xiamen's households: 1) VSACs replacing FSACs (positive impact), and 2) front-loading clothes washers replacing top-loading washers (negative impact). The impact of these two kinds of possible replacement (assuming complete replacement) on the electricity-saving technical potential in Xiamen households is summarized in Table 5.2.

Table 5.2 Appliances' Replacement Effects on the Technical Potential of Electricity Savings in Xiamen's Residential Buildings

Appliances	**Replacement Scenarios**		**Electricity Consumption Intensity** (MJ/m² ·year)		
	Scenario-I	Scenario-II	Scenario-I	Scenario-II	Change
AC[1]	Tier-1 FSAC + Tier-1 VSAC	Only Tier-1 VSAC	14.2	11.4	-2.8
Clothes Washers	Tier-1 Top-loading + Tier-1 Front-loading	Only Tier-1 Front-loading	1.7	5.7	+4.0

Note: [1] The calculation of electricity consumption is after the building envelope retrofits.

(Source: Calculation based on author's Household Energy Use Survey in Xiamen)

In Table 5.2, Scenario-I does not consider the replacement between different types of ACs or clothes washers (e.g., Tier-1 VSACs replace only current VSACs and Tier-1 FSACs replace only current FSACs), while Scenario-II considers these replacement effects (e.g., Tier-1 VSACs replace both current VSACs and FSACs).

Therefore, the changes in electricity consumption intensity between these two scenarios represent the caused impact of appliances' "replacement effects" on the electricity-saving technical potential in Xiamen's households. In summary, if such "replacement effects" are considered, the technical potential of residential electricity savings in Xiamen might be decreased by 4.0 MJ/m^2 ·year or increased by 2.8 MJ/m^2 ·year. This implies that the technical potential, in the form of a reduction percentage from the 2011 baseline level, may vary in the rage of **26.5%** to **32.5%**.

5.1.2 Potential of Natural Gas Savings

Compared with the calculation of electricity savings potential, the calculation for natural gas savings potential in Xiamen residential buildings is relatively simple as only two measures are involved. Table 5.3 shows the calculation results.

Table 5.3 Technical Potential of Natural Gas Savings in Xiamen's Residential Buildings

Measures	Thermal Efficiency (%)		2011 Baseline	Gas Savings
	Current Average	Advanced	(MJ/m^2 ·year)	(MJ/m^2 ·year)
Upgrading Gas-fired Water Heaters	88%	96%	3.5	0.26
Upgrading Built-in Type Gas Cook Stoves	51.5%	63.0%	51.8	9.46
Upgrading Desktop Type Gas Cook Stoves	56.5%	66%	35.6	5.12
		Total	**90.9**	**14.84**

(Sources: CHEAA 2014; Liu and Zhang, 2009; Zhang, 2010b; Author's Household Energy Use Survey in Xiamen)

From Table 5.3, it can be seen that the technical potential of natural gas savings in Xiamen's residential buildings is about 14.84 MJ/m^2 ·year, meaning a reduction percentage of about **16.3%** from the 2011 baseline level.

According to the Market Survey, as with the electric appliances, there also is "replacement effect" for natural gas consumption, namely built-in type stoves replacing desktop type stoves (negative impact). When considering that, the natural gas consumption intensity in Xiamen's households might increase by about 1.45 MJ/m^2 ·year, which means a drop of gas-saving technical potential from 16.3% to about **14.7%**.

5.1.3 Section Summary

Technical potential of energy savings in Xiamen's residential buildings sector is rather significant, ranging from **26.5% - 32.5%** for electricity savings, and **14.7% - 16.3%** for natural gas savings, given the uncertainties of "replacement effects" among different types of certain appliances, namely FSACs by VSACs, top-loading clothes washers by front-loading ones, and desktop type gas cook stoves by built-in type ones. When combining electricity and natural gas, the overall residential energy-saving technical potential in Xiamen will be within the rage of about **20.9%-24.9%**.

Figure 5.1 summarize the contribution of various technical measures to the residential energy-saving technical potential in Xiamen. It shows that among the various measures, those adopting efficiency-advanced gas cook stoves, refrigerators, TVs, and air conditioners, and retrofitting a building's envelope are most critical for achieving energy savings in Xiamen’s households. These five measures together account for approximate 95% of the calculated technical energy-saving potential[106].

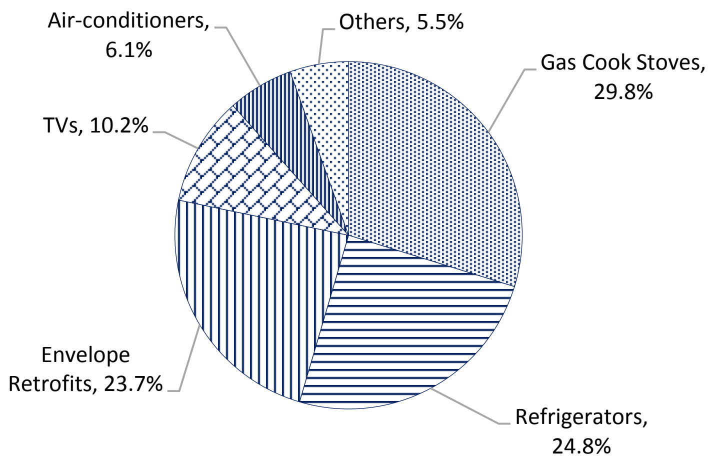

Figure 5.1 Contribution of Measures to the Technical Potential of Residential Energy Savings in Xiamen

(Source: Author’s calculation)

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[106] This potential does not consider the “replacement effects” between different types of appliances - namely FSACs by VSACs, top-loading type clothes washers by front-loading type ones, and desktop type gas cook stoves by built-in type ones.

5.2 Analysis of Economic Potential

As shown in Chapter 3, the analysis of economic potential is based heavily on the incremental cost of selected technical measures. According to the author's Market Survey (mainly about the analysis of "price-efficiency relationship" of selected energy-saving measures) presented in Chapter 4, it was found that selected technical measures could be generally divided into two categories: 1) measures that show a trend of significant price increase along with energy efficiency improvement; and 2) measures that do not show such a trend, whereby efficiency improvements can be achieved without any significant incremental costs. The economic potential analysis for these two categories of measures is shown in Sections 5.2.1 and 5.2.2 respectively.

5.2.1 Potential from the Measures without Incremental Costs

According to the author's Market Survey, there may not be any incremental costs for adopting energy efficient TVs, rice cookers, PC monitors and electric water heaters in China. In other words, the technical potential contributed by these measures could be economic potential as well, given the lack of incremental costs. According to Table 5.1, these four measures together could contribute to the reduction of electricity consumption in Xiamen's residential buildings by about 6.37 $MJ/m^2 \cdot year$, which means a reduction percentage of about **5.6%** from the 2011 baseline.

There are two main reasons why the incremental costs for these appliances (with the same capacity or size) are not significant: 1) the efficiency improvement costs of these appliances are negligible; and 2) although such costs might not be negligible, they are not correctly reflected in the appliances' pricing. As the author's Market Survey shows, the prices of rice cookers in China are mainly related to the products' appearance, functionality and display mode; the prices of electric water heaters are primarily determined by the products' control and display mode, safety measures, and adopted materials for water tanks and heating rods; the prices of TVs are mainly linked to the products' screen resolution, audio inputs, and some certain functions (i.e., Wi-Fi connection, 3D, etc.); the prices of PC monitors depend primarily on the products' screen resolution and display panel grades. In short, the pricing of these appliances is dependent on the products' other features rather than their energy efficiency. As a consequence, it is often observed that there is no positive correlation between the retail prices of these appliances and their energy efficiency levels.

Therefore, the effectiveness of financial incentives for these kinds of appliances might be much more significant than those of other kinds of appliances. Moreover, mandatory policy instruments (such as more stringent EES&L schemes) are also critical to push the production of more efficient models of these appliances.

5.2.2 Potential from the Measures with Incremental Costs

According to the author's Market Survey, other selected energy-saving measures have significant incremental costs associate with their adoption. The related incremental costs are shown in Table 4.20 of Chapter 4.

In this Section, the "Levelized Cost of Conserved Energy (LCOCE)" of adopting these measures in Xiamen's residential buildings is calculated based on Equations 3.10-3.13. As mentioned in Chapter 4, a social discount rate of 8% is adopted in this research as the reference case, while the rates of 6% and 10% are also used for "LCOCE" sensitivity analysis. The "LCOCE" calculation results for the Xiamen case are shown in Table 5.4.

Table 5.4 LCOCE of Selected Energy-Saving Measures for Xiamen's Residential Buildings

No.	Selected Measures	**Calculated LCOCE** (Yuan/kWh or Yuan/m^3)		
		6%	**8%** (reference case)	**10%**
TM-1	Retrofitting roofs	**0.7524**	**0.8790**	**1.0137**
TM-2	Retrofitting windows	2.9313	3.4245	3.9492
TM-1+2	Retrofitting both roofs and windows	2.4614	2.8755	3.3161
TM-3	Adopting Tier-2 FSAC (before implementing TM-1+2)	5.9997	6.5326	7.0860
TM-4	Adopting Tier-1 FSAC (before implementing TM-1+2)	15.3613	16.7255	18.1424
TM-5	Adopting Tier-3 VSAC (before implementing TM-1+2)	4.1814	4.5527	4.9384
TM-6	Adopting Tier-2 VSAC (before implementing TM-1+2)	4.7411	5.1622	5.5995
TM-7	Adopting Tier-1 VSAC (before implementing TM-1+2)	7.1005	7.7311	8.3860
TM-1+2+3	Adopting Tier-2 FSAC (after implementing TM-1+2)	10.1347	11.0348	11.9695
TM-1+2+4	Adopting Tier-1 FSAC (after implementing TM-1+2)	25.9481	28.2526	30.6460
TM-1+2+5	Adopting Tier-3 VSAC (after implementing TM-1+2)	7.0631	7.6904	8.3419
TM-1+2+6	Adopting Tier-2 VSAC (after implementing TM-1+2)	8.0087	8.7199	9.4586
TM-1+2+7	Adopting Tier-1 VSAC (after implementing TM-1+2)	11.9941	13.0593	14.1656
TM-8	Adopting efficiency-advanced refrigerators	**0.7516**	**0.8474**	**0.9484**
TM-9	Adopting Tier-1 front-loading clothes washers	4.5569	4.9241	5.3041
TM-10	Adopting Tier-1 top-loading clothes washers	55.4524	59.9216	64.5459
TM-11	Adopting Tier-1 gas water heaters	14.2674	15.4173	16.6071
TM-12	Adopting Anticipated Tier-1 gas cook stoves (built-in type)	**2.6623**	**2.8769**	**3.0989**
TM-13	Adopting Anticipated Tier-1 gas cook stoves (desktop-type)	**0.7568**	**0.8178**	**0.8809**

(Source: Author's calculation)

Table 5.4 reveals that there are three additional measures that are cost-effective for residential energy savings in Xiamen from the government perspective (i.e., their calculated "LCOCE" are less than the actual cost of energy in Xiamen - 1.0943 Yuan/kWh for electricity and 5.3647 Yuan/m^3 for natural gas). These measures include: 1) retrofitting roofs of buildings; 2) adopting efficiency-advanced refrigerators; and 3) adopting Tier-1 gas cook stoves.

5.2.3 Section Summary

As discussed in Sections 5.2.1 and 5.2.2, there are, in total, seven cost-effective measures for energy savings in Xiamen's residential buildings. The energy-saving potential of these measures are summarized in Table 5.5.

Table 5.5 Economic Potential of Residential Energy Savings in Xiamen

Measures	**Energy Savings** (MJ/m^2 ·year)	**Baseline Energy Consumption** (MJ/m^2 ·year)
Tier-1 TVs	4.97	8.2
Tier-1 Rice Cookers	0.51	8.5
Tier-1 PC Monitors	0.16	1.0
Tier-1 Electric Water Heaters	0.73	21.5
Retrofitting Roofs of Buildings	2.51[1]	28.5
Efficient Refrigerators	12.13	17.8
Tier-1 Gas Cook Stoves	14.58 (13.13[2])	87.4
Total	35.59 (34.14[2])	208

Note: [1] Energy consumption reduction from room air conditioners; [2] The values in the brackets are calculated by considering the "replacement effect" of desktop type gas cook stoves by built-in type ones.

(Source: Author's calculation)

From Table 5.5, given the 2011 electricity consumption intensity in Xiamen's households (113.7 $MJ/m^2 \cdot year$), the electricity-saving economic potential would be about **18.5%** (in comparison with the related technical potential of 26.5-32.5%). On the other hand, given the 2011 residential natural gas consumption intensity in Xiamen (90.9 $MJ/m^2 \cdot year$), the economic potential of natural gas savings would range from **14.4-16.0%** (in comparison with the related technical potential of 14.7-16.3%). In summary, about **57-70%** of the electricity-saving technical potential, and almost all (about **98%**) the natural gas saving technical potential in Xiamen's residential buildings are cost-effective (judged by if the relevant "LCOCE" are less than the actual cost of energy in Xiamen).

Figure 5.2 shows a comparison of the "LCOCE" values of electricity-saving measures for Xiamen's residential buildings (with a reference social discount rate of 8%)[107]. It can be seen that, in addition to the two cost-effective measures (namely retrofitting roofs of buildings and adopting efficiency-advanced refrigerators), the "LCOCE" of the other measures are generally about 3-12 times of the actual cost of electricity in Xiamen. In the other words, the low price of electricity in Xiamen makes most electricity-saving measures unattractive to stakeholders.

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[107] The measures of adopting Tier-1 FSACs and top-loading clothes washers are excluded because of their much bigger LCOCE values.

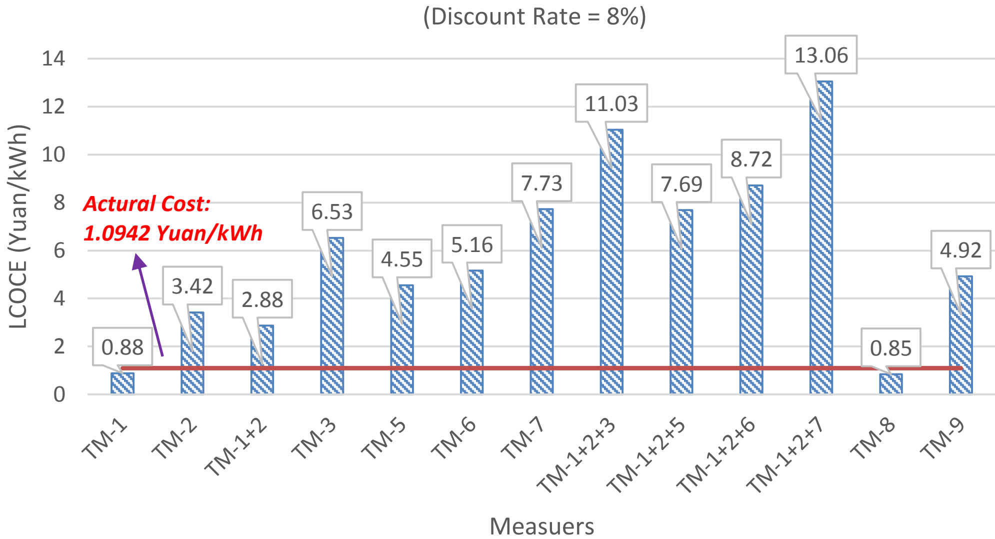

Figure 5.2 LCOCE of Residential Electricity-Saving Measures for Xiamen

(Source: Author's calculation)

Two additional things are worth noting from Figure 5.2. First, among the multiple choices of air conditioners, adopting Tier-3 VSACs, relatively, offers the best cost-effectiveness, although its "LCOCE" is still about 4.2 times the actual cost of electricity in Xiamen. Second, if the current retail prices of electricity in Xiamen could be increased to 2.3 Yuan/kWh (about 0.38 US$/kWh), the measure of retrofitting both roofs and windows of buildings would become cost-effective, which could contribute about a 10% reduction of household electricity consumption from the 2011 baseline level in Xiamen.

5.3 Analysis of Maximum Achievable Potential

As shown in Section 3.3.3 of Chapter 3, the analysis of maximum achievable energy-saving potential is based on two projections of residential energy consumption (REC), namely the business-as-usual REC (called REC-BAU) and the REC under best policy intervention[108] (called REC-BPI). The gap between the two REC projections dynamically presents the trend of "maximum achievable potential" of residential energy savings within a selected time horizon. In the Xiamen case study of this research, the REC is projected for ten years to 2020 from the baseline year of 2011.

The projections of REC-BAU and REC-BPI are implemented under two scenarios: 1) a Frozen Energy-Services-Level (FESL) Scenario; 2) an Increasing Energy-Services-Level (IESL) Scenario. The FESL Scenario assumes that people's demand levels of energy services will stay at their current levels and remain unchanged during the projection time horizon. In contrast, the IESL Scenario assumes that people's demand levels of energy services for certain end-uses may increase along with their household income growth.

It can be seen that, in the FESL Scenario, the parameter of "$\gamma_{(i,j)}$" in the Equation 3.26 (namely, the increasing rate of people's demand level of energy service "i" in the year "j") is actually given a constant of 1, while in the IESL Scenario the "$\gamma_{(i,j)}$" is given an estimated annual increase rate from the base year. For the Xiamen case study, the annual increase rate "$\gamma_{(i,j)}$" was set at 4.09% from 2011 to 2014 and 3.73% from 2014 to 2020 for electricity services (see Section 4.4.4.4 in Chapter 4).

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[108] The meaning of best policy intervention has been defined in Chapter 3. It assumes that all the new purchase of household appliances within a certain time horizon adopt the highest-efficiency products that are available in the market.

Compared with the FESL Scenario, the IESL Scenario may better reflect the realistic situation in China given the fast economic growth in the country. In addition, as the FESL Scenario is conservative in estimating energy demand, the REC-BPI projected under the FESL Scenario could indicate the lowest estimate of residential energy consumption.

To calculate the REC-BAU, the currently existing policy cases need be identified first. For the Xiamen case, these policy cases have been introduced in Section 3.3.3.5 of Chapter 3, which mainly included building energy codes (involving the JGJ75-2003 and JGJ75-2012), various EES&L schemes for appliances (involving ten types of appliances with thirteen old and new EES&L schemes, shown in Figure 3.9), and the previously-implemented one-year (2012-2013) subsidy program for efficient appliances (see details in Section 2.3.2.1). All of these policy cases are incorporated into the REC-BAU projection of this research, through adjusting relevant calculation parameters (mainly the "UEC" and "Adoption Rate" of household appliances) in the previously-structured REC projection model in Chapter 3.

Based on the collected data in Chapter 4, the REC-BAU for the Xiamen case can be projected based on Equations 3.14-3.27. Specifically in the projection, the "Simple Payback time (SPBT)" of available advanced alternative measures for a certain end-use are first calculated based on Equations 3.14-3.18. Then, the calculated "SPBT" of alternative measures are compared (see Equation 3.19), and the measure with the shortest "SPBT" is assumed to be preferred and will be purchased by a certain percentage of potential consumers (decided by the Kastovich-type adoption-decision model - see Equations 3.5-3.6). Next, the adoption rates of the "baseline option" and the "efficient option" which has the shortest "SPBT" are calculated through Equations

3.20-3.21. At last, the REC-BAU can be estimated based on these achieved adoption rates, calculated appliances vintage stocks and related "Unit Energy Consumption" through Equations 3.22-3.27.

In this research, the REC projection for the Xiamen case study specifically focuses on twelve types of household energy end-use equipment: 1) FSACs; 2) VSACs; 3) refrigerators; 4) TVs; 5) rice cookers; 6) PC monitors; 7) top-loading type clothes washers; 8) front-loading type clothes washers; 9) electric water heaters; 10) gas-fired water heaters; 11) built-in type gas cook stoves; 12) desktop type gas cook stoves. The main reasons are two: 1) the twelve types of equipment combined account for the mass majority (about 86%) of Xiamen's REC; and 2) the national EES&L schemes for them have been already issued in China (Energy Label, 2014).

In comparison, the combined energy use for lighting and other plug-in appliances, and the use from heat and renewable energy only account for about 14% of Xiamen's REC. In this research, the REC projection for them does not assume energy efficiency improvements, and is calculated by multiplying associated energy use intensities with equipment (or housing) stock values.

The detailed REC-BAU projection results for the Xiamen case are summarized in Tables B-1 and B-2 of Appendix B. The aggregated projection results are shown in Figures 5.3 (for the FESL Scenario) and 5.4 (for the IESL Scenario). In Figures 5.3 and 5.4, the REC-BAU is aggregated by the five household energy end-use groups, namely space cooling, plug-in appliances, water heating, lighting, and cooking.

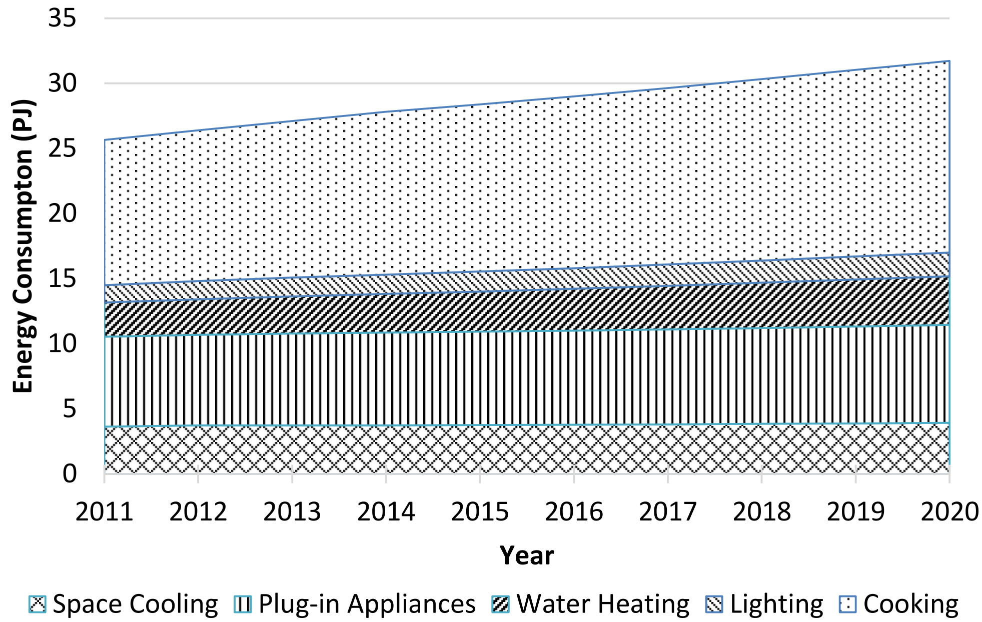

Figure 5.3 Projected REC-BAU in Xiamen (FESL Scenario)

(Source: Author's calculation)

From Figure 5.3, it can be observed that, under the FESL Scenario, the total REC-BAU in Xiamen will be about 31.7 PJ (petajoule) in 2020, which is 23.7% higher than that in the baseline year of 2011 (implying an average annual increase rate of about 2.4% within the ten years). Specifically, the BAU residential electricity consumption in Xiamen may increase to 4543.8 GWh in 2020, which is 16.7% higher than the baseline year level (implying an average annual increase rate of about 1.7% from 2011 to 2020); the BAU residential natural gas consumption in Xiamen may grow to 14.8 PJ in 2020, which is 31.9 % higher than that in 2011 (implying an average annual increase rate of about 3.1% over the ten years).

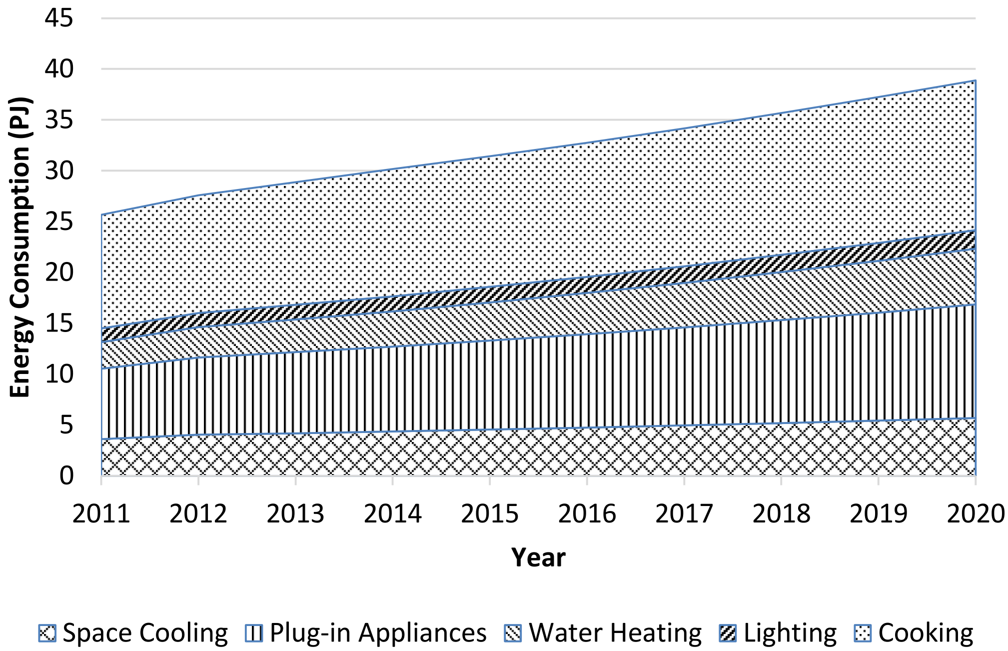

Figure 5.4 Projected REC-BAU in Xiamen (IESL Scenario)

(Source: Author's calculation)

From Figure 5.4, it can be found that the total REC-BAU under the IESL Scenario in Xiamen will be 38.9 PJ in 2020, which is 51.5 % higher than that of the baseline year of 2011 (implying an annual increase rate of about 4.7% from 2011 to 2020). Specifically, the BAU residential electricity consumption in Xiamen may increase to 6446.8 GWh in 2020, which is about 65.5% higher than that in 2011 (implying an annual increase rate of about 5.8% during the decade). Xiamen's BAU residential natural gas consumption in 2020 will be almost the same with that calculated under the FESL scenario, namely about to 14.8 PJ[109].

The projection of REC-BPI is similar to that of REC-BAU but simpler. As the REC-BPI assumes that only the measures with the highest-efficiency are adopted by consumers in their new purchases, the Kastovich-type adoption-decision model will then not be applied. The REC-BPI could be calculated through Equations 3.14 through 3.26, and Equation 3.28. It is worth noting that the "direct rebound effects" of adopting efficient measures on energy savings are reflected in the projection of REC-BPI through the coefficient of "$\varphi_{(i,j)}$" in Equation 3.28 (see details in Section 3.1.2).

The detailed projection results of REC-BPI are summarized in Tables B-3 and B-4 of Appendix B. As with the REC-BAU, the projection results of Xiamen's REC-BPI are also aggregated by the five household energy end-use groups, as shown in Figure 5.5 (for the FESL Scenario) and 5.6 (for the IESL Scenario).

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[109] In this research, it is assumed that people's demand level of energy service for cooking in Xiamen households will not increase along with their income growth.

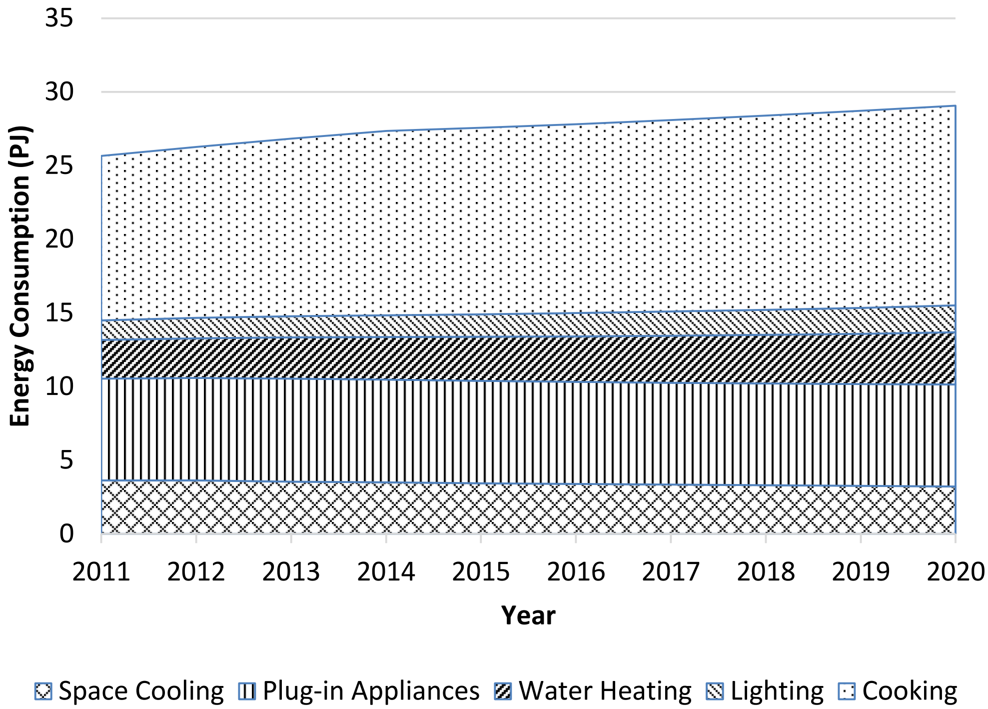

Figure 5.5 Projected REC-BPI in Xiamen (FESL Scenario)

(Source: Author's calculation)

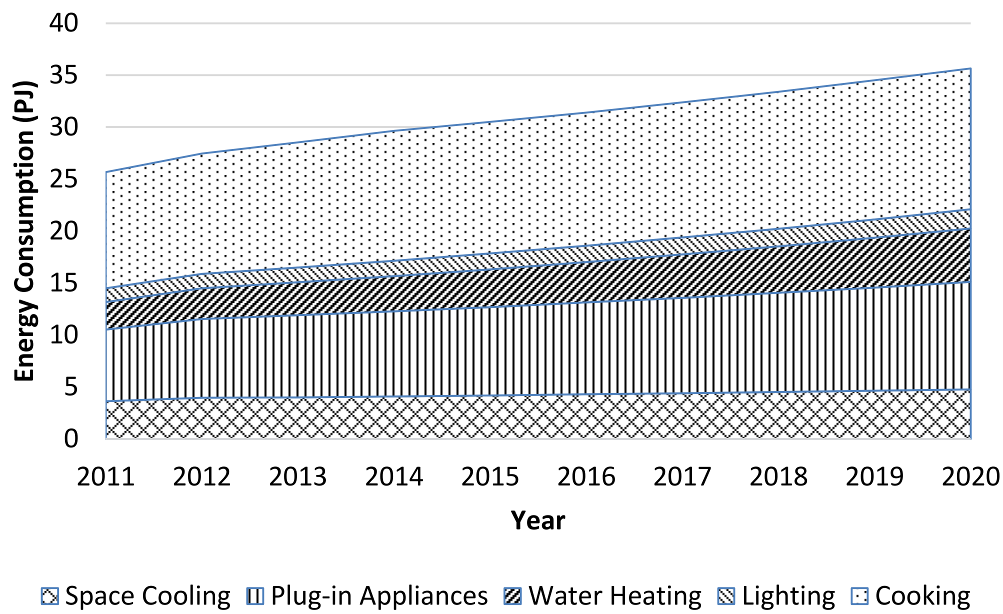

Figure 5.6 Projected REC-BPI in Xiamen (IESL Scenario)

(Source: Author's calculation)

Figures 5.5 and 5.6 show that, with the "best policy intervention," Xiamen's REC in 2020 will be about 29.1 PJ under the FESL Scenario or 35.7 PJ under IESL Scenario. Specifically, the residential electricity consumption in Xiamen in 2020 may be about 4126.6 GWh under the FESL Scenario or 5873.7 GWh under the IESL Scenario; the residential natural gas consumption in Xiamen in 2020 may be about 13.62 PJ under the FESL Scenario or 13.64 PJ under the IESL Scenario. Given Xiamen's 2011 residential electricity consumption (3894.4 GWh) and natural gas consumption (11.2 PJ), it can be observed that there will still be a significant increase in both electricity and natural gas consumption in Xiamen's residential buildings sector during the period from 2011 to 2020.

Based on the above projected REC-BAU and REC-BPI in Xiamen, the "maximum achievable potential" of energy savings in Xiamen's residential buildings sector during the time horizon of 2011-2020 was estimated, as shown in Table 5.6.

Table 5.6 Maximum Achievable Potential of Residential Energy Savings in Xiamen

Year	FESL Scenario			IESL Scenario		
	REC-BAU (PJ)	**REC-BPI** (PJ)	**MAP** (%)	**REC-BAU** (PJ)	**REC-BPI** (PJ)	**MAP** (%)
2011 (base year)	25.66	25.66	n/a	25.66	25.66	n/a
2012	26.39	26.26	0.51%	27.60	27.46	0.51%
2013	27.11	26.82	1.09%	28.87	28.54	1.12%
2014	27.80	27.34	1.68%	30.16	29.64	1.73%
2015	28.38	27.55	2.92%	31.42	30.50	2.94%
2016	28.99	27.80	4.12%	32.75	31.41	4.11%
2017	29.64	28.07	5.27%	34.17	32.38	5.24%
2018	30.32	28.38	6.38%	35.66	33.41	6.33%
2019	31.03	28.72	7.45%	37.25	34.50	7.38%
2020	31.73	29.06	8.39%	38.88	35.65	8.30%

Note: MAP stands for the "maximum achievable potential," and it is expressed in the form of a reduction percentage from the related REC-BAU (see Equation 3.29).

(Source: Author's calculation)

Table 5.6 reveals that the accumulated maximum achievable energy savings in Xiamen's residential buildings during the period of 2011 to 2020 could be 11.39 PJ under the FESL Scenario, or 13.28 PJ under the IESL Scenario. This energy-saving amount is equal to about 44.4% (the FESL Scenario), or 51.8% (the IESL Scenario) of the Xiamen's 2011 REC. It is worth noting the fact that a larger potential of energy savings may be related to a larger consumption of energy. Therefore, in some cases, a performance evaluation based only on achieved energy savings may be not very meaningful or even misleading.

The calculation results in Table 5.6 also clearly show the dynamic trend of "maximum achievable potential (MAP)" of residential energy savings in Xiamen, which reflects the real-world "ramping-up adoption progress" of advanced technical measures. In the form of a reduction percentage from the REC-BAU at the same year, the MAP in Xiamen will keep increasing until the projection year 2020. In the first year (i.e., 2012), the MAP is about 0.5% for both FESL and IESL scenarios, while in 2020 it will increase to about **8.4%** under the FESL Scenario, or **8.3%** under the IESL Scenario. The calculated MAP expressed in the form of a reduction percentage from the relevant BAU consumption level are quite close, even though different development scenarios of people's demand level of household energy services are assumed.

The calculated MAP provides policymakers with valuable information for making feasible local energy development or climate change mitigation plans. As an example, by comparing the REC-BPI under the FESL Scenario in 2020 (i.e., 29.06 PJ) with Xiamen's REC in the base year of 2011(i.e., 25.66 PJ), it can be seen that, even with the most ideal assumptions (i.e., people's demand level of household energy services stay unchanged at the base year level, and all their new purchases of appliances adopting the most efficient models), the total of Xiamen's REC in 2020 will still be about **13.3%** higher than that of 2011. This result clearly indicates that for the evaluation period of 2011-2020, Xiamen's total REC (or related carbon emissions) will be still growing even with the best policy intervention. Thus, a plan of controlling Xiamen's total REC (or related carbon emissions) will not be feasible yet at least before 2020.

Electricity and natural gas are the two dominant types of energy utilized in Xiamen's residential buildings. Figures 5.7 and 5.8 respectively present the projected residential electricity and natural gas consumption in Xiamen during the projection period of 2011-2020.

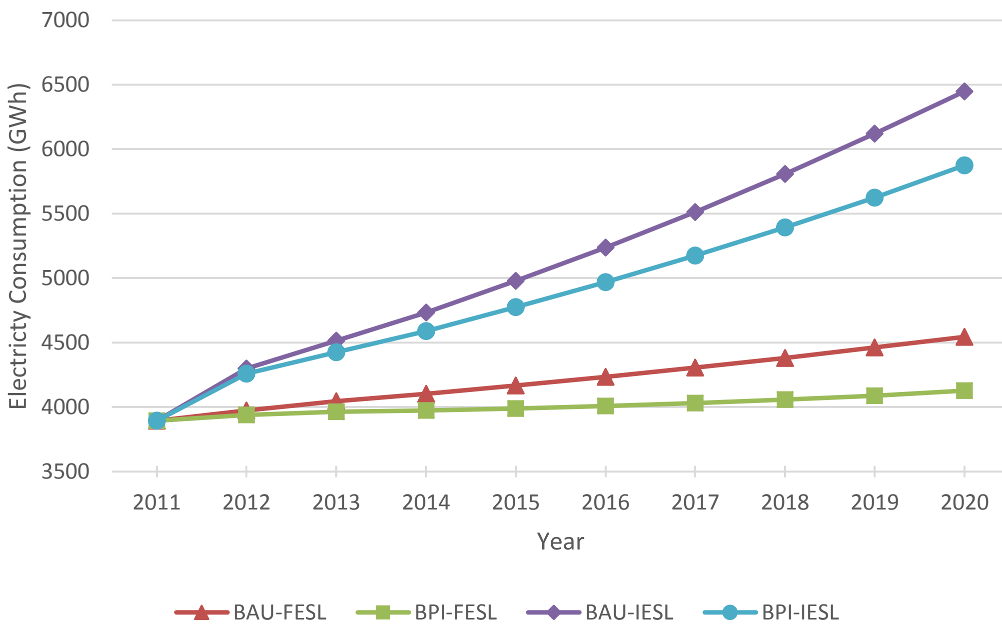

Figure 5.7 Projected Residential Electricity Consumption in Xiamen

(Source: Author's calculation)

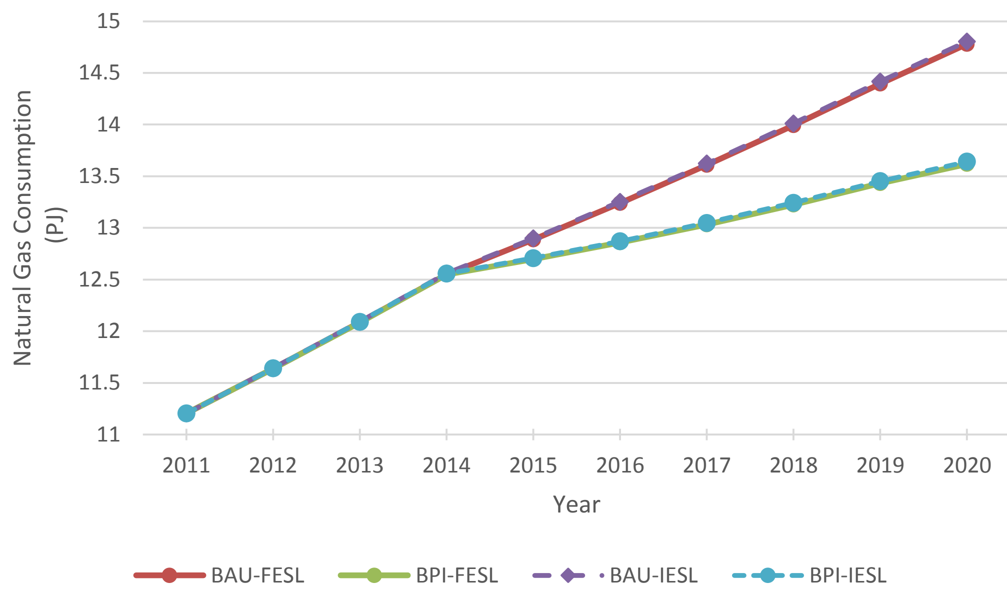

Figure 5.8 Projected Residential Natural Gas Consumption in Xiamen

(Source: Author's calculation)

In Figure 5.7 and 5.8, the gaps between the related BAU curves and BPI curves visually present the dynamic "maximum achievable potential" of energy savings in Xiamen's residential buildings sector. These gaps imply the full potential of residential electricity or natural gas savings in Xiamen which are left for incentive policy interventions. For natural gas consumption projection, the curves of BAU-FESL and BAU-IESL (the same with the curves of BPI-FESL and BPI-IESL) overlap quite a bit (see Figure 5.8). This is mainly because cooking (by gas-fired cook stoves) accounts for the dominant share (about 99.6%) of natural gas use in Xiamen's households, and people's demand level of energy service for cooking in the City is thought to be unchanged along with their income growth (THUBERC, 2013). The gap between the BAU and BPI curves will occur in 2015 (the two curves were overlapped from 2011 to 2014). The reason is because China's first-ever EES&L scheme for gas-fired cook stoves is going to be enforced at that time.

5.4 Analysis of Possible Achievable Potential

5.4.1 To-Be-Tested Policy Intervention Cases

As shown in Section 3.3.3.5 of Chapter 3, based on a comprehensive assessment of China's current energy-saving policies for buildings, four types of policy interventions are identified as appropriate and feasible for promoting residential energy savings in Xiamen before 2020. These include building energy codes, EES&L schemes for household appliances, subsidy to efficient appliances, and energy pricing.

Section 3.3.3.5 also considered the realistic feasibility of these four types of policy interventions in Xiamen, and developed ten "to-be-tested" policy intervention cases. These "to-be-tested" policy cases are utilized for the calculation of "possible achievable potential (PAP)" of residential energy savings in Xiamen. The PAP calculation results could provide policymakers with valuable information on evaluating the real-world impact of different policy interventions on residential energy savings. Table 5.7 summarizes the ten "to-be-tested" policy intervention cases.

Table 5.7 To-Be-Tested Policy Intervention Cases for the Xiamen Case Study

Policy Type	Policy Instrument	Policy Case	Details of Policy Case
Mandatory	Building Energy Codes	New Code (N-BEC)	15% reduction of cooling load from the current code JGJ75-2012; Revised in 2018;
	EES&L Schemes for Appliances	New EES&L-Refrigerator (N-EES&L-R)	15% efficiency improvement from the current scheme GB12021.2-2008; Revised in 2018;
		New EES&L-AC (N-EES&L-AC)	15% efficiency improvement from the current schemes GB21455-2013 and GB12021.3-2010; Revised in 2018;
		New EES&L-TV (N-EES&L-TV)	15% efficiency improvement from the current scheme GB24850-2013; Revised in 2018;
Financial	Subsidy to Efficient Appliances (SEA)	SEA-10	Subsidy = 10% of products' retail prices; Applied to efficient ACs (Tier-1 and 2), refrigerators (Tier-1), and cook stoves (Tier-1); Enforced during 2016-2020;
		SEA-20	Subsidy = 20% of products' retail prices; Applied to efficient ACs (Tier-1 and 2), refrigerators (Tier-1), and cook stoves (tier-1); Enforced during 2016-2020;
		SEA-30	Subsidy = 30% of products' retail prices; Applied to efficient ACs (Tier-1 and 2), refrigerators (Tier-1), and cook stoves (Tier-1); Enforced during 2016-2020;
	Energy Pricing (EP)	EP-1	Price = RP + EX (i.e., electricity: 0.5543 Yuan/kWh; NG: 4.1047 Yuan/m^3); Enforced during 2016-2020;
		EP-2	Price = RP + GS (i.e., electricity: 1.0478 Yuan/kWh; NG: 5.26 Yuan/m^3); Enforced during 2016-2020;
		EP-3	Price = RP + EX+ GS; (i.e., electricity: 1.0943 Yuan/kWh; NG: 5.3647 Yuan/m^3); Enforced during 2016-2020;

Note: *RP*, *GS* and *EX* respectively stand for the current regulated retail prices of energy, government subsidies to energy, and the carbon emissions costs of energy.

(Sources: Author's assessment based on Tu, 2010; Kang, 2008; Cai, 2006; CHEAA, 2011; TOP10, 2012; Li et al., 2013; CBEEX, 2013; XCG, 2013; XCG, 2011; IEA, 2012; CEC, 2012; EPA, 2014)

Among these assumed "to-be-tested" policy intervention cases, the revision of EES&L schemes in this research focuses on three types of important household appliances, namely refrigerators, TVs and ACs. According to the author's Xiamen Household Energy Use Survey, together they account for almost half of the electricity consumption in Xiamen's households. Considering the usual revision cycle of building energy codes and EES&L schemes in China, the time horizon of 2018-2020 is adopted for implementing these "to-be-tested" mandatory policy cases.

The assumed subsidy programs for efficient appliances target three key types of efficiency-price sensitive appliances (i.e., refrigerators, air conditioners, and gas cook stoves), which together consume about 64% of total residential energy consumption in Xiamen. In addition, there are three schemes structured for energy pricing (see more details in Sections 3.3.3.5 and 4.4.3). The period of 2016-2020 is used as the time horizon for enforcement of these "to-be-tested" financial policy cases.

5.4.2 Analysis Results

As shown in Chapter 3, the estimates of "possible achievable potential (PAP)" of energy savings completely depend on the structured "to-be-tested" policy intervention cases which are appropriate and feasible for the selected case study. Under different policy intervention cases, the "*UEC*" and "*AR*" for household energy end-use measures vary, and consequently result in different REC projection results. By comparing these projection results with the REC-BAU, the PAP under different policy intervention cases can be observed. As with the MAP analysis, the PAP analysis is also performed under the FESL and IESL scenarios.

5.4.2.1 Influences of Mandatory Policy Cases

The projected energy savings (namely the PAP) under the assumed mandatory policy intervention cases are respectively presented in Figures 5.9 (the FESL Scenario) and 5.10 (the IESL Scenario).

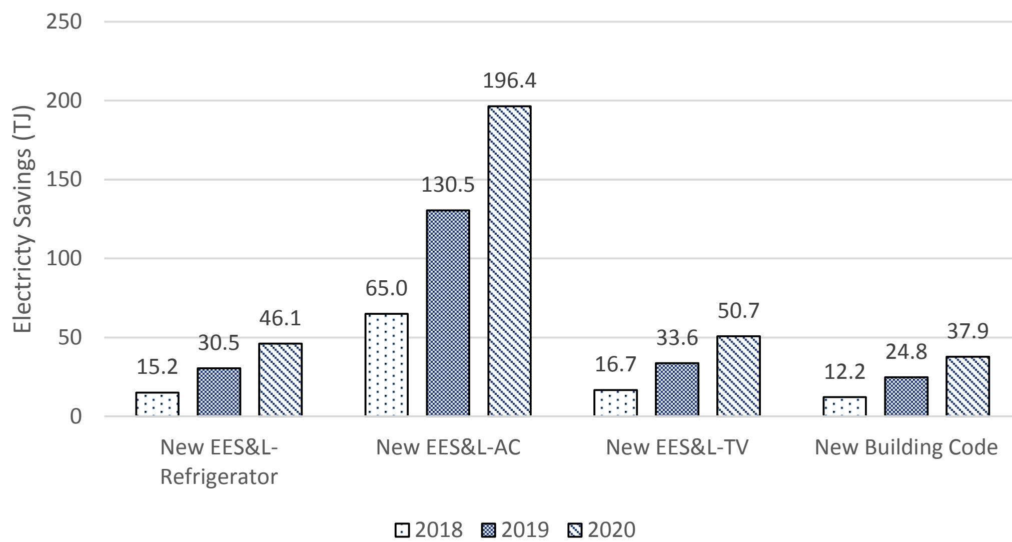

Figure 5.9 Projected Residential Electricity Savings in Xiamen under the Assumed Mandatory Policy Cases (FESL Scenario)

(Source: Author's calculation)

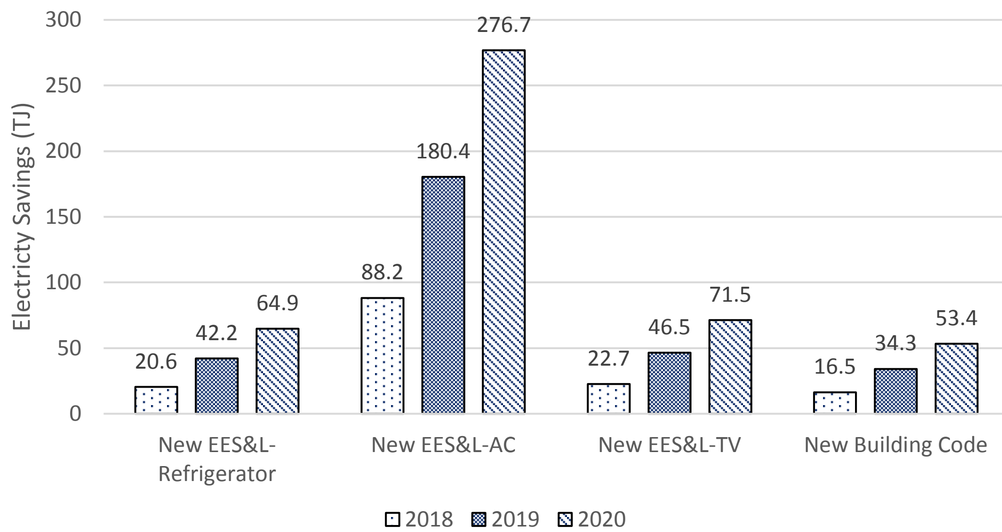

Figure 5.10 Projected Residential Electricity Savings in Xiamen under the Assumed Mandatory Policy Cases (IESL Scenario)

(Source: Author's calculation)

Figures 5.9 and 5.10 show that the EES&L schemes could result in an accumulated electricity savings of about **584.9** TJ under the FESL Scenario, or **813.8** TJ under the IESL Scenario from 2018 to 2020, once they are enforced in 2018 (an relatively aggressive schedule according to the usual revision cycle of EES&L schemes for appliances in China). These possible savings are equal to about **4.2%** (the FESL Scenario) or **5.8**% (the IESL Scenario) of Xiamen's total residential electricity consumption in 2011. In comparison, the building energy code could lead to much less accumulated electricity savings, about **74.9** TJ under the FESL Scenario or **104.2** TJ under the IESL Scenario during the same period, which are respectively about **0.53%** and **0.74%** of Xiamen's total residential electricity use in 2011.

The above analysis results reveal that, given Xiamen's climate characteristics and the operation mode of air conditioners (usually not for 24 hours and not for all rooms), upgrading the current building energy code only makes limited contributions to electricity savings, particularly compared to tightening the EES&L scheme for air conditioners. Therefore, to effectively reduce residential energy consumption in southern China (particularly in the HSWW climate zone), the EES&L schemes for main household appliances (particularly for air conditioners) should be given priority over stricter building energy codes.

5.4.2.2 Influences of Subsidy Programs to Energy Efficient Appliances

Under the FESL Scenario, the projected energy savings under assumed subsidy cases are presented respectively in Figures 5.11 (SEA-10), 5.12 (SEA-20) and 5.13 (SEA-30).

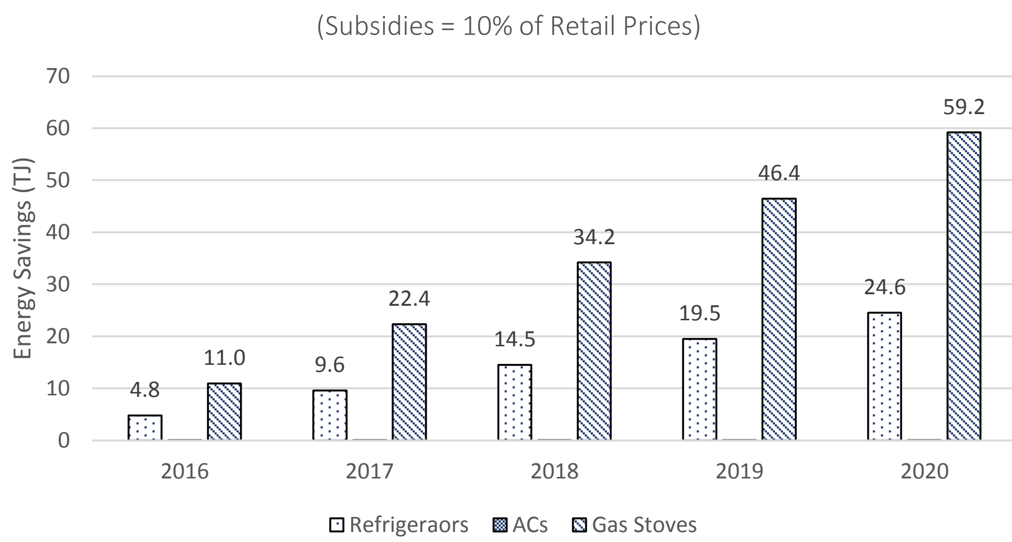

Figure 5.11 Projected Residential Energy Savings in Xiamen under the Assumed Policy Case of SEA-10 (FESL Scenario)

(Source: Author's calculation)

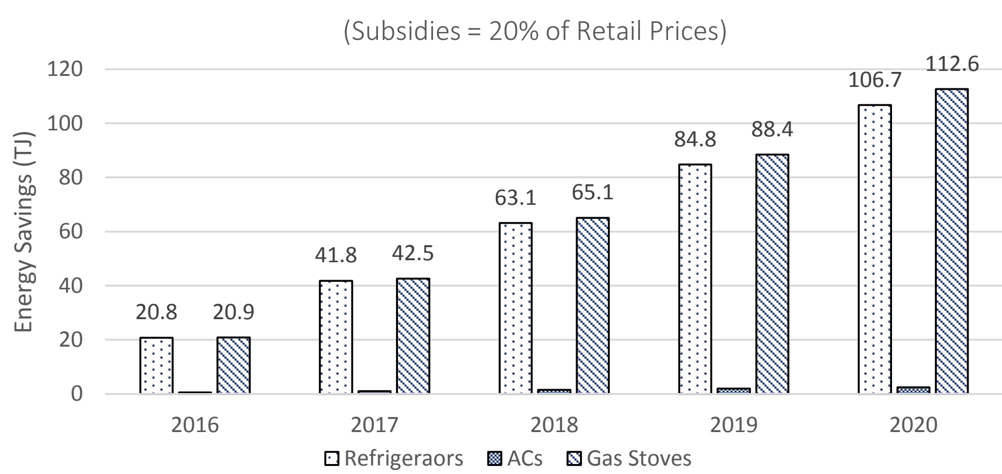

Figure 5.12 Projected Residential Energy Savings in Xiamen under the Assumed Policy Case of SEA-20 (FESL Scenario)

(Source: Author's calculation)

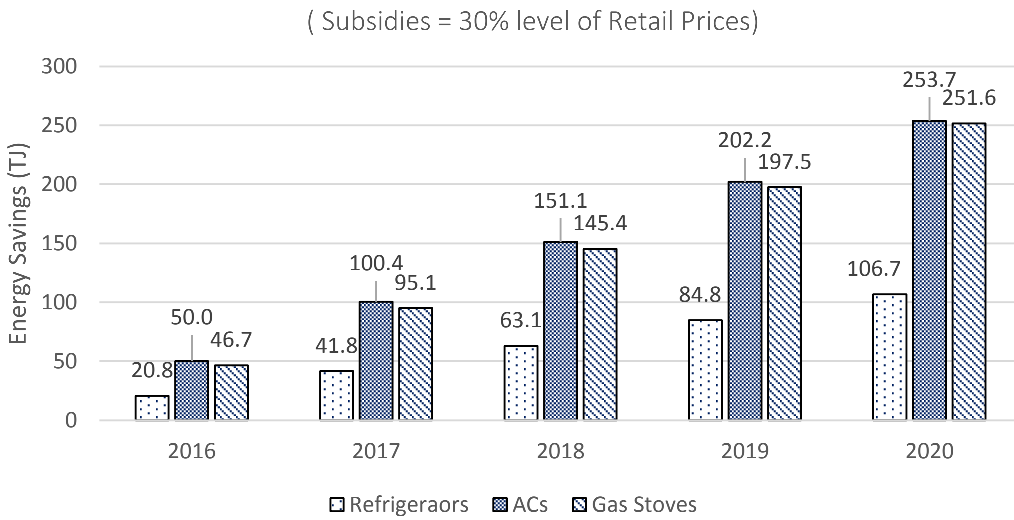

Figure 5.13 Projected Residential Energy Savings in Xiamen under the Assumed Policy Case of SEA-30 (FESL Scenario)

(Source: Author's calculation)

Figures 5.11, 5.12 and 5.13 reveal the appropriate subsidy levels for different kinds of appliances. For air conditioners, subsidy levels between 10% and 20% of their retail price would hardly result in any energy savings, while a subsidy level of 30% of their retail price could bring significant energy savings - about increasing by 50.7 TJ per year in Xiamen from 2018-2020. For refrigerators, a subsidy level of 20% of their retail price is quite effective, while a higher subsidy level would be a waste of financial resources. As for gas stoves, a subsidy increase of 10% to 30% of their retail price would lead to larger energy savings.

Under the IESL Scenario, the projected energy savings under the assumed subsidy cases are presented respectively in Figures 5.14 (SEA-10), 5.15 (SEA-20) and 5.16 (SEA-30).

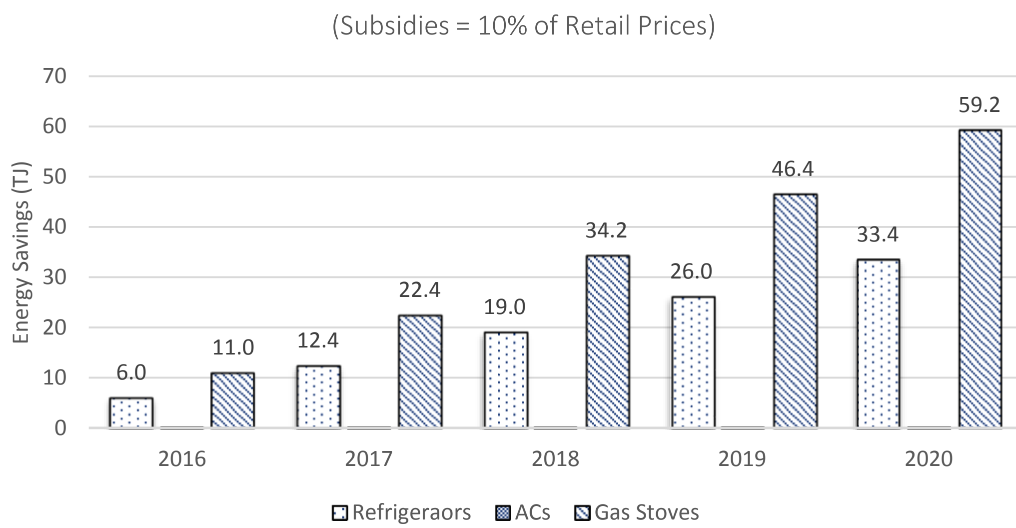

Figure 5.14 Projected Residential Energy Savings in Xiamen under the Assumed Policy Case of SEA-10 (IESL Scenario)

(Source: Author's calculation)

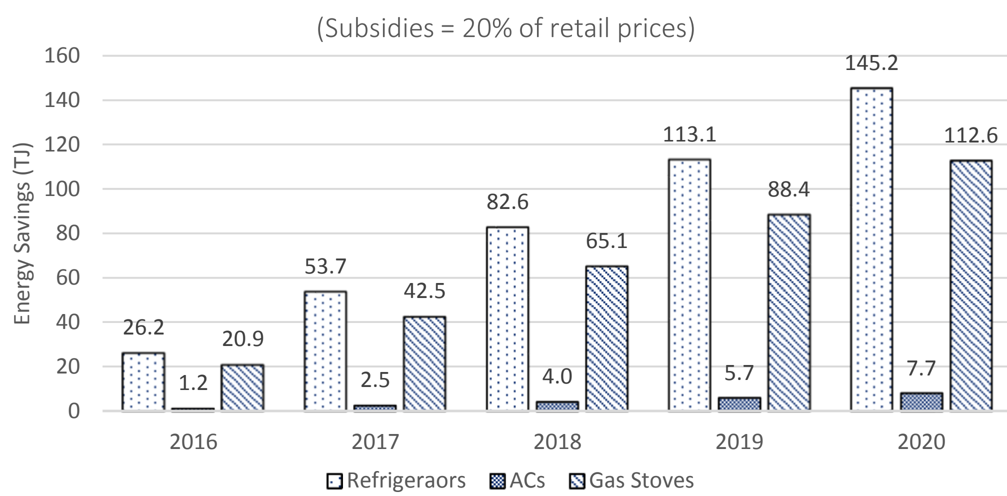

Figure 5.15 Projected Residential Energy Savings in Xiamen under the Assumed Policy Case of SEA-20 (IESL Scenario)

(Source: Author's calculation)

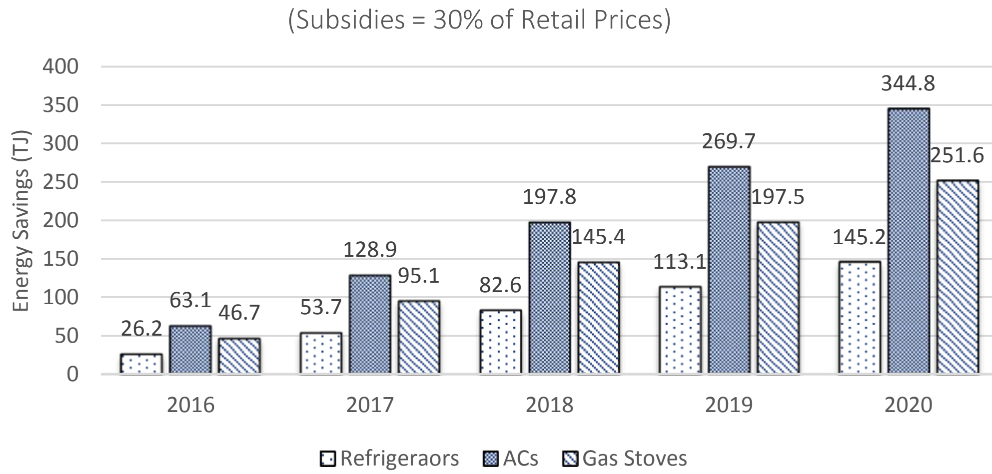

Figure 5.16 Projected Residential Energy Savings in Xiamen under the Assumed Policy Case of SEA-30 (IESL Scenario)

(Source: Author's calculation)

Figures 5.14 through 5.16 reveal that under the IESL Scenario the appropriate subsidy levels for these three kinds of appliances are similar to the observations under the FESL Scenario. For air conditioners, a 30% subsidy of the products' retail price, would increase electricity savings by about 69.0 TJ yearly under the IESL Scenario (about 18.3 TJ larger than that under the FESL Scenario). For refrigerators, a 20% subsidy of the products' retail price would increase electricity savings about 29.0 TJ yearly under the IESL Scenario (about 7.7 TJ larger than that under the FESL Scenario). Since it is assumed in this research that the demand level of energy service for cooking remains unchanged, the projected energy savings for gas cook stoves are the same under the FESL and IESL scenarios.

In summary, to design effective subsidy programs for efficient appliances, the subsidy levels must be specifically tailored for different appliances to avoid being ineffective on energy savings or wasting financial resources. There is no "one-size-fits-all" subsidy level. In other words, the appropriate subsidy level for a certain appliance needs to be carefully calculated based on multiple factors, including the incremental cost and energy efficiency levels of available advanced options of the appliance, local energy prices, market shares of different types of the appliance, local use patterns of the appliance, etc.

5.4.2.3 Influences of Energy Pricing Schemes

The influences of higher energy prices on energy consumption are generally reflected through two different mechanisms: 1) higher energy prices make consumers purchase more efficient household appliances; and 2) higher energy prices make consumers reduce their use of appliances. In this section, the influence of higher energy pricing by the first mechanism on energy savings is analyzed for the Xiamen case study based on Equations 3.14 through 3.27.

The policy intervention cases of EP-1, EP-2 and EP-3 are used for the analysis. As listed in Table 5.7, the ER-1 case adds the "carbon emissions costs" of energy over the current energy retail price (RP); the EP-2 case adds the "hidden government subsidies" to energy over the current RP; the EP-3 case adds both of the "carbon emissions costs" and "hidden government subsidies" over the current RP. It is worth noting that the calculated energy savings in this section is a conservative estimate since the second mechanism in which consumers reduce their use of household appliances is not reflected in the calculation.

The projected energy savings under the assumed energy pricing cases are shown in Figures 5.17 (the FESL Scenario) and 5.18 (the IESL Scenario).

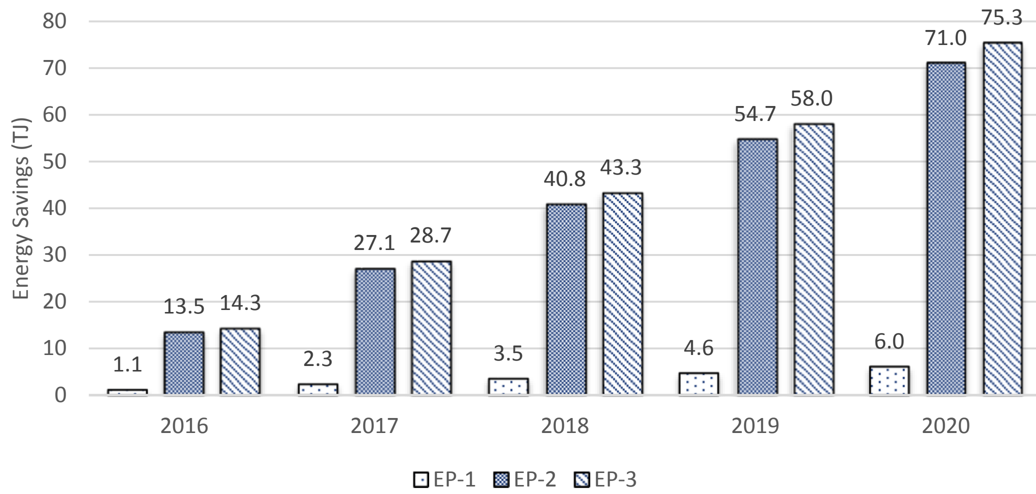

Figure 5.17 Projected Residential Energy Savings in Xiamen under the Assumed Energy Pricing Cases (FESL Scenario)

(Source: Author's calculation)

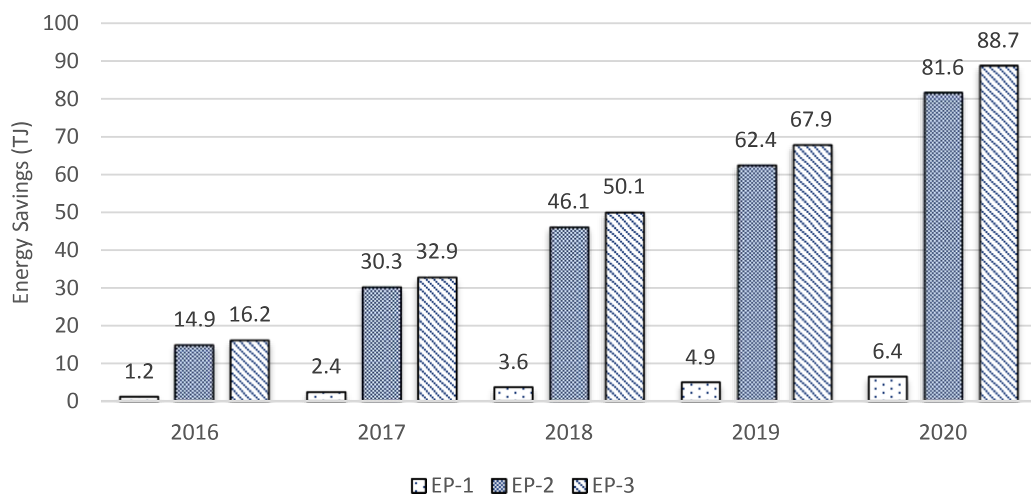

Figure 5.18 Projected Residential Energy Savings in Xiamen under the Assumed Energy Pricing Cases (IESL Scenario)

(Source: Author's calculation)

Figures 5.17 and 5.18 show that: 1) by adding the environmental externality costs of energy over the current energy retail prices (electricity and natural gas) in Xiamen, about 1.2-1.3 TJ of residential energy use could be reduced annually; 2) by adding the hidden government subsidies to energy over the current energy retail prices, about 14.2-16.3 TJ of energy could be saved annually in Xiamen's households; and 3) by adding both the environmental externality cost of energy and the hidden government subsidies to energy over the current energy retail prices, a bit larger portion amounting to 15.1-17.8 TJ of Xiamen's residential energy consumption might be annually conserved.

From the calculation results, it can be seen that the energy savings under the policy case of EP-1 is not significant. This is because the involved environmental externality costs (i.e., carbon emissions costs) of energy in China is very low (about 9.2% of electricity's retail price and 2.6% of the retail price of natural gas for the Xiamen case). Except for carbon emissions (whose trading price is at a lower level in recent years), the other kinds of pollutants related to energy use (such as SO_x and NO_x) are not being traded in China yet (CBEEX, 2013). In comparison, the government subsidies to energy production in China are significant (about 106.3% of the electricity retail price and 31.5% of the retail price of natural gas for the Xiamen case) (Li et al., 2013). Therefore, as shown in the policy case of EP-2, in order to effectively promote residential energy savings in China, removing the "hidden government subsidies" to electricity and natural gas needs to be given a high priority.

For energy pricing interventions, it is worth noting that, for normal goods (like electricity and natural gas), increase in energy prices might result in decrease in energy demand and consumption. This effect is not considered in this dissertation. In fact, due to the regulated utility market in China (energy prices are often fixed for number of years), there is no historical data to build reliable econometrics models which could help to evaluate price elasticities of demand for electricity and natural gas in the nation.

5.4.2.4 Section Summary

Based on the above calculation results, Table 5.8 summarizes the estimated "possible achievable potential" of energy savings in Xiamen's residential buildings sector under the assumed ten "to-be-tested" policy intervention cases. It must be noted that, the energy savings shown in Table 5.8 represent the annual additional energy savings (using the energy savings in the previous year as the baseline), in order to compare the energy-saving impact of different policy intervention cases.

Table 5.8 Average Annual Additional Residential Energy Savings in Xiamen under the Assumed Policy Intervention Cases

Policy Intervention Cases[1]	Average Annual Additional Energy Savings[2] (TJ/year)	
	FESL Scenario	IESL Scenario
New EES&L for Refrigerators (N-EES&L-R)	15.36 [15.15-15.58]	21.65 [20.56-22.76]
New EES&L for ACs (N-EES&L-AC)	65.48 [65.03-65.94]	92.24 [88.24-96.32]
New EES&L for TVs (N-EES&L-TV)	16.91 [16.74-17.09]	23.83 [22.71-24.96]
New Building Energy Code (N-BEC)	12.60 [12.18-13.09]	17.80 [16.52-19.12]
SEA-10	16.75 [15.76-16.75]	18.52 [17.00-20.11]
SEA-20	44.35 [42.13-44.35]	53.09 [48.20-58.25]
SEA-30	122.41 [117.48-122.40]	148.32 [135.90-161.31]
EP-1	1.20 [1.14-1.39]	1.28 [1.19-1.49]
EP-2	14.20 [13.46-16.33]	16.32 [14.91-19.19]
EP-3	15.07 [14.28-17.34]	17.75 [16.20-20.87]

Note: [1] The details of these policy intervention cases are shown in Table 5.7; [2] The annual additional energy savings use the energy savings in the previous year as the baseline; the values in square brackets show the range of annual additional savings from the start year (2016 for mandatory cases or 2018 for financial cases) to the end year (2020).

(Source: Author's calculation)

Table 5.8 clearly reveals that: 1) upgrading the current building energy code would only make limited contributions to residential electricity savings in Xiamen, particularly compared to tightening the EES&L scheme for air conditioners; 2) with low implementation costs, regularly tightening the EES&L schemes for main household appliances would cause significant residential energy savings in Xiamen (in the whole of China as well), particularly compared with subsidy programs for efficient appliances; 3) among the assumed policy intervention cases, the residential energy-saving potential from raising the current energy retail prices in Xiamen by adding the "carbon emissions costs" of energy use or removing the "hidden government subsidies" to energy production are not that impactful, which is mainly because current energy retail prices in China are intentionally regulated at a low level, and the incremental costs of most energy-saving measures for Chinese residential buildings are still quite significant; and 4) generally, subsidy programs for efficient appliances can cause significant energy savings, especially if the subsidy level is set to be about 20% of the retail prices of main household appliances. However, it must be noted that there is no "one-size-fits-all" subsidy level. In order to avoid being ineffective on energy savings or wasting financial resources, the appropriate subsidy level for a certain appliance needs to be carefully calculated based on Equations 3.14 through 3.27 in Chapter 3.

From the above calculation results (see Figure 5.9-5.18), it can be found that the possible achievable potential of residential energy savings in total (namely a combination of the assumed four types of policy interventions) in Xiamen in 2020 could be about 712.5-1310.1 TJ under the FESL Scenario, and about 966.2-1697.5 TJ under the IESL Scenario. The low-limit value of the savings range is achieved based on the combination of the policy interventions of "N-BEC, N-EES&L-R, N-EES&L-AC, N-EES&L-TV, SEA-10 and EP-1," while the high-limit value is based on the combination of the policy interventions of "N-BEC, N-EES&L-R, N-EES&L-AC, N-EES&L-TV, SEA-30 and EP-3." Given the fact that the REC-BAU of Xiamen in 2020 is projected to be about 31.73 PJ under FESL Scenario and 38.88 PJ under IESL

Scenario (see Table 5.6), the possible achievable potential of residential energy savings (in the form of a reduction percentage from the BAU level) in Xiamen in 2020 will be roughly about 2.3-4.1% under the FESL Scenario, or about 2.5-4.4% under the IESL Scenario. In summary, roughly only **one-fourth** to **one-half** of the maximum (or theoretical) achievable potential in Xiamen in 2020 will possibly be achieved by implementing current appropriate and feasible incentive policies.

5.5 Chapter Summary

This Chapter provides a comprehensive residential energy-saving potential analysis for the Xiamen case study in southern China, based on the methodology presented in Chapter 3 and data collected in Chapter 4. It includes "technical potential," "economic potential," "maximum achievable potential," as well as the "possible achievable potential" under diverse assumed policy interventions.

As the household energy consumption for cooking, lighting, water heating, plug-in appliances and even space cooling do not vary much across the urban cities in China (THUBERC, 2013), the study case of Xiamen also provides a representative example in which to observe the residential energy-saving potential excluding those from centralized space heating in urban China.

First, the potential analysis for the Xiamen case found that there is a significant technical potential of energy savings about **20.9%-24.9%** in Xiamen's residential buildings sector. Specifically, the technical potential of electricity savings is about **26.5%-32.5%**, while it is about **14.7%-16.3%** for natural gas savings[110].

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[110] The range of technical potential is caused by considering or not considering the "replacement (or substitution) effects" among different types of certain appliances.

Second, it was found that about **57%-70%** of the electricity-saving technical potential and almost all (about **98%**) of the natural gas savings technical potential in Xiamen's residential buildings sector can be viewed as cost-effective from the government (or society) perspective. The cost-effectiveness in this research was judged by comparing the calculated "levelized cost of conserved energy (LCOCE)" of available advanced technical measures to the "actual cost" of conserved energy. The "actual cost" of energy in this research was defined by adding the "carbon emissions costs" of energy use and the "hidden government subsidies" to energy production over the current retail prices of energy. As the research takes the government perspective, an appropriate "social discount rate" was adopted for the "LCOCE" calculation - 8% for reference analysis, and 6% and 10% respectively for sensitivity analysis.

Next, by mainly referring to the EIA's (2013) NEMS-RDM, a residential energy consumption (REC) projection model specifically tailored for southern China was developed (see Equations 3.14 through 3.29 in Chapter 3). With this REC projection model, the achievable potential analyses for the Xiamen case can be implemented. This model can function as a policy analysis tool to quantitatively evaluate the real-world impact of diverse policy interventions (mandatory, financial or even awareness-attitude educational incentives) on residential energy savings in southern urban China.

Then, based on the proposed REC projection model, the dynamic trend of "maximum achievable potential (MAP)" of residential energy savings in Xiamen within the time horizon from 2011 to 2020 was estimated. The results showed that the MAP in Xiamen in 2020 (in the form of a reduction percentage from the BAU level of REC at the same year) can reach only to about **8.3%-8.4%** under two different development scenarios of people's demand level of household energy services. The two scenarios are: 1) the FESL (Frozen Energy-Service-Level) Scenario which assumes that people's demand level of household energy services remains unchanged at the base year level during the projection period; and 2) the IESL (Increasing Energy-Service-Level) Scenario which assumes that people's demand level of household energy services increases along with the growth of their household income – the increase rates for the Xiamen case study were estimated mainly based on the "Econometric Model" suggested by Swisher et al. (1997) (see details in Section 4.4.4.4 of Chapter 4). The MAP calculation results also showed that, even with the most ideal assumption (i.e., people's demand level of household energy services remaining unchanged at the base year level, and all new purchases of appliances adopting the most efficient models), the Xiamen's total REC in 2020 will be still about **13.3%** higher than that of the base year 2011. This finding clearly implies that for the period of 2011-2020, Xiamen's total REC (or related carbon emissions) will be still growing even with the best policy interventions. In other words, at least before 2020, the energy conserved through promoting energy efficiency improvements for appliances in Xiamen's households would not be enough to offset the residential energy consumption increase caused by added housing stock (mainly driven by population growth) in the city. This fact might be different in some developed countries (ACEEE, 2012).

Finally, based on an assessment of China's current energy-saving incentive policies for buildings (presented in Chapter 2), four types of policies were analyzed for being appropriate and feasible for promoting energy savings in Xiamen's households: namely building energy codes, EES&L schemes for appliances, subsidy programs for efficient appliances and energy pricing. Accordingly, ten “to-be-tested” policy intervention cases (listed in Table 5.7) were structured for analyzing the “possible achievable potential (PAP)” of energy savings in Xiamen’s residential buildings sector. As with the MAP analysis, the analysis of PAP was also performed under the two scenarios of FESL and IESL. The PAP analysis results for the Xiamen case found that “tightening the EES&L schemes for ACs” and “subsidizing the purchases of energy efficient appliances (with a subsidy level of 20-30% the appliances’ retail prices)” could result in significant residential energy savings in Xiamen. The results also showed that only **one-fourth** to **one-half** of the maximum (or theoretical) achievable potential in Xiamen in 2020 will possibly be achieved by implementing current incentive policies. This finding clearly reveals that in order to realize higher achievable residential energy-saving potential in China, the Chinese governments need to introduce more new, innovative and market-based incentive policies (e.g., tax incentives, awareness-attitude educational programs, deregulated utility market, establishing trading system for pollutants like NOx and SOx, etc.).

Chapter 6

CONCLUSIONS AND FUTURE RESEARCH

Due to China's population size, robust economic growth and fast urbanization, residential energy consumption in China is enormous, and rapidly increasing. Serious environmental degradation and global warming threats have led the Chinese central government to actively pursue sustainable energy strategies. With the revision of the *Energy Conservation Law of China* in 2008, promoting energy savings from residential buildings has been expedited in China. This underscores the need to design effective policies, which is the central research focus of this dissertation.

To deal with this research focus, this dissertation explores effective policy intervention opportunities in southern China through analyzing residential energy-saving potential, using the city of Xiamen as a case study. Previous research on Chinese residential energy-saving potential was focused mainly on technical potential. In this dissertation, a comprehensive potential analysis was implemented, covering four types of potential: technical potential, economic potential, maximum achievable potential, and possible achievable potential. Different analysis serves different policymaking needs. All four types of potential analysis could provide policymakers with valuable information for the design of effective policy interventions.

Referring mainly to the EIA's (2013) *Residential Demand Module* of the *National Energy Modelling System* (*NEMS*), a computational model estimating dynamic achievable potential (maximum and possible) was developed. This computational model has not been studied in China yet. The proposed computational model for achievable potential analyses in this dissertation can be used as a policy analysis tool to quantitatively evaluate the real-world impact of diverse policy incentives (e.g., building energy codes, EES&L schemes for appliances, various financial incentives, and even awareness-attitude educational programs, etc.) on residential energy savings for southern China cities.

Although the city of Xiamen was used as the case study in this dissertation, the proposed methodology (including conceptual framework, analytical approaches, and data collection methods) can be applied to any other city in southern China, or the cities in northern China as long as the energy-saving potential from centralized space heating is excluded from the analysis. It is worth noting that as the energy use patterns for lighting, cooking, plug-in appliances, water heating and space cooling do not vary much among Chinese cities (THUBERC, 2013), the Xiamen case can represent the overall electricity and gas consumption structure in Chinese urban residential buildings.

In 2009, at the Copenhagen Climate Change Conference (COP15), the Chinese government announced its commitment to greenhouse gas (GHG) emissions, with a pledge to reduce the amount of GHG emitted per unit GDP by 40-45% from the 2005 level by 2020 (WRI, 2009). In 2014, during U.S. President Obama's visit to China, President Xi of China further announced that China had established a target to have its GHG emissions peak around 2030 (White House, 2014), and would further lower its GHG emissions per unit GDP by 60-65% from the 2005 level by 2030 (UNFCCC, 2015). These significant commitments request strong and wide actions from not only the Chinese central government but also local governments at different levels on energy savings. By using the city of Xiamen as a case study, this dissertation explored to what extent energy-saving policymaking in the Chinese residential buildings sector could contribute to the nation's commitment to the global community for GHG reduction.

This Chapter comprises two sections. Section 1 summarizes the conclusions based on the research findings from the China policy review (see Chapter 2) and potential analysis for the Xiamen case study (see Chapter 5). Section 2 presents the limitations of this study and the work left for future research.

6.1 Research Findings and Conclusions

6.1.1 From the Policy Review

A comprehensive review and assessment of China's current energy-saving incentive policies for buildings was presented in Chapter 2. This review primarily aimed at identifying and structuring policy intervention cases for the targeted dynamic achievable energy-saving potential analyses. Nonetheless, it provided extensive and important information for improving the current incentive policies. In the review, it was found that China at present relies mainly on four types of incentive policies: building energy codes, financial incentives, a green building rating scheme, and EES&L schemes for household appliances. The research findings and conclusions for further improving these incentive policies are introduced below.

- **Building Energy Codes**

Through continuous policymaking efforts from 1986 to 2007, China established a nearly complete building energy codes system for residential buildings, including three design codes for different climate zones (JGJ26, JGJ134 and JGJ75), and one acceptance code (GB50411) targeting the construction stage of buildings. All the design codes adopt “dual-procedure” mechanisms for compliance (i.e., both prescription and performance approaches adopted), which give China’s building industry more flexibility in the application of innovative energy-saving technologies in buildings. With the issuance of the acceptance code (GB50411) in 2007, the installation of energy-saving measures in Chinese buildings has become a prerequisite (like requirements for fire protection) for putting buildings into operation. As a consequence, the building energy codes compliance rate in China has been significantly improved from about 50% in 2006 to about 95% in 2010 (Tu, 2010; MOHURD, 2007-2010). Nevertheless, there are still two obvious defects with China’s building energy codes system. The first relates to the long revision cycle of codes (usually 10 years or more), which might significantly impede the timely adoption of emerging energy-saving technologies in buildings. The second is linked to the fact that the code revision is not institutionalized, and this can be observed through the erratic launch mechanisms and working team establishment practices for code revisions.

- **Financial Incentives**

A few financial incentives have been implemented in China for energy savings in buildings. With the exception of the newly implemented “multistep electricity pricing” in 2012, all were about subsidy programs. In short, the financial incentives adopted in China are not diversified. Since subsidy programs depend completely on governments’ annual appropriation from their budget, these subsidy incentives cannot serve China's commitment to promote residential energy savings on both a stable and long-term basis. For example, China's sole subsidy program for efficient appliances was implemented only for one year (2012-2013). Therefore, China should start to explore the adoption of more market-based financial incentives for buildings, such as tax incentives (e.g., rebates, credits, etc.), sustainable energy utilities (SEU), revolving loan funds, energy efficiency credit of commercial banks, etc. China's heavy dependence on subsidy programs may be mainly for two reasons. First, due to the influence of the past central-planning economy system, the Chinese governments prefer command-and-control based incentives over market-based ones. Second, China lacks sufficient "institutional capacity" (e.g., mature taxation system, banking system, financial market, etc.) to implement more complex market-based financial incentives.

- **The Green Building Rating Scheme**

China's first-ever green building rating scheme (called the 3-Star scheme) was implemented in 2007. This research, however, found that this scheme might not contribute much to China's residential energy savings primarily because of the weak criteria that applied to a building's energy performance. Moreover, as a voluntary information tool, the market penetration of the 3-Star scheme in China is quite low. From 2007 to 2011, only a total of 376 buildings received the rating label (Schroeder, 2013). The low market penetration of China's 3-Star scheme might be explained to a great extent by its weak criteria. As achieving an increased reputation from receiving a rating is often the primary reason stakeholders (e.g., investors or building owners) apply for building rating labels, a relatively weak rating scheme could largely discourage motivation, particularly when there are strong competitors in the market (e.g., the U.S. LEED in China's building rating market). Therefore, strengthening the evaluation criteria of China's 3-Star scheme should be a priority for policymakers. In addition, as building's energy performance is often only a small part in a green building rating scheme (such as China's 3-Star and the U.S. LEED), China may consider an additional specific "energy-focused" building rating scheme along with its 3-Star scheme. A good example is the "Energy Performance Certificate (EPC)" system currently implemented in Germany (DENA, 2014).

- **EES&L Schemes for Household Appliances**

As the result of continuous policymaking efforts during the past ten years, China has established a comprehensive "Energy Efficiency Standard and Labelling (EES&L)" system for household appliances, covering the main appliances such as refrigerators, air conditioners, TVs, clothes washers, water heaters, rice cookers, gas cook stoves, etc. With this mandatory EES&L policy, an energy label must be placed on every appliance product for sale in the Chinese market. The energy efficiency (or performance) data displayed on the label provides information that consumers can use to make their purchase decisions. However, the realistic effect of the energy labels might be significantly impeded by the energy efficiency (or performance) information contained on them for two reasons. First, the efficiency information shown on the labels for some appliances (e.g., TVs, PC monitors, and fixed-speed air conditioners) is difficult for ordinary consumers to understand. Second, for some appliances (e.g., refrigerators, variable-speed air conditioners, clothes washers), although the presented information is comprehendible to ordinary consumers, it could be designed better to aid consumers in their decision-making process. For example, for refrigerators, the presented efficiency information on the energy label is *kWh/24 hours*. However, the presentation of annual consumption, *kWh/year*, may have a more significant impact, and thus increase the likelihood of consumers selecting more efficient products. Further, it was even proposed that the products' total energy consumption over their whole lifetime should be displayed on the energy label (TOP10, 2012). Since consumers are more sensitive to the "money value" (i.e., saved energy cost) of an efficiency improvement than the efficiency improvement itself, the U.S. "EnergyGuide" label shows another way to encourage consumers' purchases of efficient appliances by presenting "estimated yearly operating cost" on the label (DOE, 2014).

6.1.2 From the Potential Analysis

Residential energy-saving potential analysis could provide policymakers with valuable information for the design of effective intervention policies. In this dissertation, the methodology for analyzing the technical, economic and achievable residential energy-saving potential for southern China was established (see Chapter 3) and based mainly on the EPA's (2007) *Guide for Conducting Energy Efficiency Potential Studies*, the EIA's (2013) *NEMS-RDM*, and the Kastovich (1982) type adoption-decision model of advanced technical measures. The proposed methodology was applied to the city of Xiamen in southern China as a case study. Based on the potential analysis for the Xiamen case study (see Chapter 5), several important conclusions related to the design of effective intervention policies for southern China are made as follows.

- **Gas cook stoves, air conditioners and refrigerators are three critical household appliances for residential energy savings in China, and should be given priority in policymaking.**

According to the author's Household Energy Use Survey in Xiamen (see Section 4.1 in Chapter 4), these three household appliances together account for about two-thirds (64.3%) of the total residential energy consumption in the City (see more details in Figure 4.6). The survey showed that a Xiamen household, on average, consumes about 19.5 GJ of energy annually. Broken down by end-uses, cooking's share of energy use in Xiamen's households is about 42%, followed by plug-in appliances (25.6%), space cooling (13.7%), water heating (13.7%) and then lighting (5%). As the energy consumption intensities for these five end-use groups do not vary much across cities in China (THUBERC, 2013), the pattern of Xiamen's household energy use is a typical example of that in other Chinese cities (excluding the energy use for centralized space heating in northern China, which is a special case under the current Chinese context).

- **There exists a significant technical potential for residential energy savings in China.**

From the potential analysis for the Xiamen case study (presented in Chapter 5), it was found that there is a significant technical potential of residential energy savings about **20.9-24.9%** in the city. Specifically, for electricity savings the technical potential is about **26.5-32.5%**, while for natural gas savings it is about **14.7-16.3**%. To achieve this significant technical potential, certain technical measures are critical, including: 1) retrofitting the envelope of buildings; and 2) adopting efficient gas cook stoves, refrigerators, TVs, and air conditioners. According to the author's calculation, these five technical measures together could account for approximate 95% of the estimated technical potential of residential energy savings in Xiamen.

However, it is worth noting that implementing building envelope retrofits is very challenging in urban China primarily because of the dominant housing type, which is high-rise apartment buildings. It is difficult to reach an agreement among the numerous housing units owners to invest in building envelope retrofits (CSTC, 2010). Moreover, a significant portion of the housing units in urban China (about 30%) are occupied by tenants, not owners. This raises the so-called "principal-agent" problem, which makes part of the housing units owners have no initiatives at all to invest in building retrofits. As a consequence, achieving residential energy savings in southern China should focus primarily on the adoption of efficient household appliances, particularly the four types noted: refrigerators, TVs, air conditioners and gas cook stoves.

- **A large share of the significant technical potential of residential energy savings in urban China is cost-effective from the government perspective.**

It was found that about **57-70%** of the electricity-saving technical potential and almost all (about **98%**) of the natural gas savings technical potential in Xiamen's residential buildings sector could be viewed as cost-effective. The cost-effectiveness was judged by comparing the calculated "levelized cost of conserved energy"

(LCOCE) of available advanced technical measures with the "actual cost" of conserved energy. This research was based on the governments' perspectives, which involve two key principles. The first one is that an appropriate "social discount rate" was adopted for the calculation of "LCOCE." The second is that the "actual cost" of energy was adopted, defined in this research by adding the "environment externality costs" of energy use and the "hidden government subsidies" to energy production over the current retail prices of energy. The economic potential analysis in this research found that, owing to the low energy price and significant up-front cost, many currently available advanced technical measures in China are not cost-effective, and their calculated "LCOCE" are often several times the "actual cost" of energy.

- **The "maximum achievable potential" analysis of residential energy savings could provide policymakers with valuable information for making feasible energy development or climate change mitigation plans.**

The achievable potential of residential energy savings was estimated based on an established residential energy consumption (REC) projection model (see Equations 3.14-3.29 in Chapter 3). The projection results showed that the "maximum achievable potential" (MAP) of residential energy savings in Xiamen will keep increasing from about 0.5% in 2012 to about **8.3-8.4%** in 2020 mainly because of the realistic "gradual ramping-up adoption progress" of advanced technical measures. In addition, the analysis found that, even with the most ideal assumptions (i.e., people's demand level of household energy services remains unchanged at the base year level, and all new purchases of appliances adopt the most efficient models), the total REC in 2020 for

Xiamen will still be about **13.3%** higher than that of the base year, 2011. This clearly implies that for the period of 2011-2020, Xiamen's total REC (or related carbon emissions) will be still growing even with the best policy interventions. In other words, at least before 2020, the energy conserved through promoting energy efficiency improvements for appliances in Xiamen's households would not be enough to offset the REC increase caused by added housing stock (mainly driven by population growth) in the City. Therefore, a plan to control Xiamen's total REC (or related carbon emissions) at the 2011 level will not be feasible at least by 2020.

- **The "possible achievable potential" analysis of residential energy savings can be used as a policy analysis tool to quantitatively evaluate the real-world impact of divers incentive policies (e.g., mandatory, financial or even educational programs) on residential energy savings.**

To design effective intervention policies for residential energy savings, it is critical to quantitatively evaluate the realistic energy-saving impact of optional policy interventions. The "possible achievable potential" (PAP) analysis proposed in this research was used to meet this need.

The PAP analysis for the Xiamen case study (see Section 5.4.2 in Chapter 5) revealed critical information for the design of effective intervention policies for residential energy savings in southern China. These included:

1. Upgrading the current building energy code (to reduce the cooling load of buildings) would only make limited contributions to residential electricity

savings in Xiamen. In comparison, regularly tightening the EES&L schemes for main household appliances (such as refrigerators, TVs and air conditioners) would result in significant energy savings in the city (in the whole of China as well). Therefore, of the two main mandatory incentive policies in China (i.e., building energy codes and EES&L schemes for appliances), the incentive of EES&L schemes for appliances should be given priority in policymaking for saving residential energy use in southern China.

2. To design effective subsidy programs for efficient appliances, the subsidy levels must be specifically tailored for different appliances to avoid being ineffective on energy savings or waste financial resources. In China, a subsidy of 10% to 20% of the retail prices for air conditioners would hardly cause any energy savings, while a subsidy level equaling 30% of their retail price could bring significant energy savings; for refrigerators, a 20% subsidy level is quite effective, while a higher subsidy level would be a waste of financial resources; for gas stoves, an increase in subsidies from 10% to 30% would lead to larger energy savings. In short, there is no "one-size-fits-all" subsidy level. The appropriate subsidy level for a certain appliance needs to be carefully calculated based on multiple factors, including the incremental cost and energy efficiency levels of available advanced options of the appliance, local energy prices, market share of different types of the appliance, and local use patterns of the appliance (see Equations 3.14 through 3.27 in Chapter 3).

3. The residential energy-saving potential from raising the current energy retail prices in Xiamen by adding the "carbon emissions costs" of energy use or removing the "hidden government subsidies" to energy production are not impactful. The main reason is because the current energy retail prices in China are intentionally regulated at a low level, and the up-front costs of most energy-saving measures for Chinese residential buildings are still quite significant.

4. Since the current carbon emissions cost in China is quite low, about 8.7 US$/ton (CBEEX, 2013), the energy pricing strategy of adding this environmental externality cost would be ineffective on residential energy savings. In contrast, government subsidies to energy production in China are relatively significant (Li et al., 2013). Therefore, in order to effectively promote residential energy savings in China, removing the "hidden government subsidies" to electricity and natural gas need to be given high priority by the policymakers dealing with energy pricing strategies. The abolition of fossil fuel subsidies could show the administration's ambition to achieve sustainable development (Bengtsson et al, 2015).

5. Roughly only **one-fourth** to **one-half** of the maximum (or theoretical) achievable potential in Xiamen in 2020 might possibly be achieved by implementing current appropriate and feasible incentive policies. Therefore, in order to realize larger achievable residential energy-saving potential in China, the Chinese governments should introduce more new,

innovative and market-based incentive policies (e.g., tax incentives, awareness-attitude educational programs, deregulated utility market, establishing trading system for pollutants like NOx and SOx, etc.).

6. As learned from the PAP analysis for the Xiamen case study, it is worth noting that a higher level of energy consumption often means a more significant level of possible energy-saving potential. Therefore, one should always pay careful attention to the "context" of any energy-saving potential analysis, and avoid being misled by the analysis results (Swisher et al., 1997).

6.2 Direction for Future Research

There are some limitations related to this dissertation research, and they might be the future research work, introduced as follows.

- **Improving the Residential Energy Consumption (REC) Projection Model**

As shown in this dissertation, the dynamic achievable potential analyses (maximum and possible) of residential energy savings were primarily based on REC projections. To project the REC, a computational model is needed. In this dissertation, an REC projection model specifically tailored for cities in southern China was developed based on a broad literature view. However, restricted mainly by data availability, the structured REC projection model must involve some key sub-models or assumptions, which could be further improved in the future for better REC projection. They are discussed below.

1. Improving the Kastovich-type Adoption-Decision Model

The core for REC projection, to a great extent, lies in the selected people's adoption-decision making model of advanced technical measures. In this dissertation, a Kastovich (1982) type adoption-decision model was utilized. This model has been used by the NREL (2010) for modeling PV market size in the U.S., and by the EIA (2013) in its "National Energy Modeling System (NEMS)." In this Kastovich-type adoption-decision model, it is assumed that individuals' adoption rate of an advanced measure increases along with their perceived decrease of the "simple payback time (SPBT)" of that measure[111].

However, the single "SPBT" factor may not completely cover all of the significant aspects that factor into people's adoption-decision making process of advanced technical measures. According to the research in the fields of "social psychology" and "technology adoption theories" (Rogers, 1995; Ajzen, 1991), other factors such as the effect of social norms on energy savings, moral incentives, and information communication channels all play an important role on people's adoption-decision making. Therefore, as a future research topic, it may be much better to take them into account as well, and then structure a multiple-factor adoption-decision model for REC projection. Such research has not been implemented in China according to the author's literature review.

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[111] It is worth noting that the "SPBT" is a complex factor whose calculation involves the energy price, the conserved energy amount from baseline technical measures, the related financial incentives, and the incremental cost from baseline measures.

2. Projecting People's Demand Level of Energy Services in a Non-aggregated Way

According to Swisher et al. (1997), people's demand level of household energy services along with their income growth is a key socioeconomic factor for REC projection. The concept of people's demand level of energy services is implicit, and often difficult to measure (the measurements are also specific for end-uses). Thus, a credible projection of the changes of people's demand level of energy services often faces the challenge of a lack of related data.

In this dissertation, the projection of people's future demand level of household energy services is based on an econometric model (see Equation 4.22 in Chapter 4). In it, the level of household income and energy price make the final decision on people's demand level of household energy services. However, such an econometric model is aggregated in nature, and can be used only to project the change of overall demand level of household energy services. In other words, the changes in demand levels of energy service for diverse household end-uses (e.g., space cooling, refrigerators, TVs, etc.) are not able to be obtained through this type of econometric model.

Therefore, in order to more accurately project the REC in China, studying the trends of people's demand levels of energy service for diverse household end-uses (by field testing, developing specific regression models, etc.) is desired, and this should be an important future research topic.

3. Studying Direct Rebound Effects of Energy Efficiency Improvements for China Cases

As mentioned in Chapter 3, “direct rebound effects” are an important concept related to energy efficiency improvements (IRCG, 2013; ACEEE, 2012; Ouyang et al., 2010). Therefore, in order to more accurately project REC, the “direct rebound effects” caused by adopting diverse energy efficiency measures are worth studying. According to Lin and Liu (2015), the “direct rebound effects” of energy consumption in China’s residential buildings sector, however, have been rarely studied.

In this dissertation, to project the REC under the scenario of “best-policy-intervention” (which assumes that all the new purchases of appliances adopt the most efficient models) for the Xiamen case study, the scales of “direct rebound effects” for diverse household energy end-uses (e.g., space cooling, water heating, TVs, etc.) were all obtained from a related research in the U.S. (ACEEE, 2012). As the scales of “direct rebound effects” are closely related to local context (e.g., income level, energy price level, operation mode of appliances, etc.), the scales of “direct rebound effects” for household energy use in China may be, to some extent, different from those observed in the U.S. context. In this sense, studying the scales of “direct rebound effects” for diverse household energy end-uses in China is much worth to be a future research topic.

- **Studying Economy-wide Rebound Effects of Energy Consumption for China Cases**

In addition to direct rebound effects of efficiency improvements, economy-wide (or called indirect) rebound effects should also be a future study. For example, people may cook less at home but eat out more often at restaurants as their income increase; the saved energy cost from adopting efficient household appliances may be used by people for purchasing more gasoline for driving. These cases mean that there is energy consumption transfer between different sectors (e.g., from the residential sector to the commercial or transport sector). Therefore, for examining the overall energy savings in China from a more holistic perspective, studying economy-wide rebound effects of adopting efficient household appliances should be given adequate research attention in the future.

- **Analyzing the Residential Energy-Saving Potential in Northern China Cities**

This dissertation focuses primarily on southern China cities, although the proposed methodology can be also applied to analyze the residential energy consumption excluding for space heating in the cities in northern China. The main reason is because the centralized space heating (by boiler plants or combined heat and power plants) used in northern China has long been viewed by the general public as an important piece of government-provided social welfare and thus is unique and complex for energy-saving potential analysis and policy interventions (see the discussion in Section 1.3 of Chapter 1). Since centralized space heating in northern

China account for about 24.2% of China's total residential energy consumption (THUBERC, 2013), studying the northern China cases is worth additional research in the future.

- **Studying the Inclusion of More Environmental Externality Costs in Energy Pricing**

This dissertation found that the energy price for households in China is too low to effectively encourage people's favorable energy use behaviors. Even adding the carbon emission costs of energy use and removing hidden government subsidies to energy production, most of the significant energy-saving measures for Chinese residential buildings are still cost-ineffective, from the perspective of government or society. Therefore, in future study, more environmental externality costs of energy use should be taken into account for the economic potential analysis of residential energy use. These environmental externality costs may include the pollutant emissions costs of particulates, sulfur oxides and nitrogen oxides, and even the health care costs related to them

- **Studying More Market-based Financial Incentives for China**

The policy review in this dissertation showed that, currently, the financial incentives for China's residential energy savings are not diversified. Most of the issued financial incentives are about subsidy programs (see Section 2.3.2 in Chapter 2), which are not stable or sustainable. Therefore, given the fact that the initial costs are often a major barrier to implementing energy efficiency investments and enormous funds are needed in China, exploring long-lasting market-based fundraising mechanisms for energy efficiency financing is very important and worth being studied. These topics include revolving loan fund (Indvik et al., 2013), energy efficiency bonds (like the establishment of Sustainable Energy Utility) (Byrne et al., 2008), and energy efficiency credit of commercial banks (World Bank, 2010), and so on.

- **Integrated Policy Analysis to more Effectively Influence Policymakers**

This dissertation focuses specifically on the design of effective intervention policies for residential energy savings in the cities of southern China. In practice, from a more holistic perspective, the local policymakers (e.g., the mayors) usually consider integrated approaches to resolve complex development issues facing their cities. This particularly requires the integration of energy policies with other important sustainable development or environmental protection policies. Therefore, in order to effectively and successfully engage local policymakers in action, the integrated policy analysis is worth additional future research work. Integrated policy analysis may include incorporating residential energy-saving interventions into the strategies for sustainable cities (or called eco-cities), and studying co-benefits from energy savings for climate change and air pollution, etc.

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Appendix A

QUESTIONNAIRE OF XIAMEN HOUSEHOLD ENERGY USE SURVEY

1. <u>Basic Housing Information</u> (9 questions)

1.1 You are the: 1) Owner 2) Tenant

1.2 The floor space of your house is_______m^2.

1.3 When was your house/building constructed?

1) Before 1970 2) 1970s (1971-1980) 3) 1980s (1981-1990)

4) 1990s (1991-2000) 5) after 2000

1.4 Type of your house is:

1）One-floor bungalow 2）Apartment (2~6 floors)

3）Tower-type apartment (≥7floors) 4）Slab-type apartment (≥7floors)

5）Villa

1.5 If you live in an apartment,

It is on the No. ______Floor of a building with a total of_____ floors.

1.6 The main orientation of your house is:

1） Northern-Southern 2）Western-Eastern 3）Northern

4） Southern 5）Eastern 6）Western

7） other_____

1.7 Residents in your house (please also click the person who is interviewed in behalf of the family)

Residents	**Age**	**Occupation**	**Education Level**	**If the interviewee?**
Father (or Male Owner)				
Mother (or Female Owner)				
Children				
Grandfathers				
Grandmothers				
Other Relatives				
Friends				
Nannies				
Others______________				

1.8 Room information

Room Type	Living Room	Bedroom	Study Room	Kitchen	Bathroom	Dining Room	Other Room
Amount (if no, write zero)							

1.9 What's the average household MONTHLY INCOME?

1) ≤ 2,000 Yuan 2) 2,001~4,000 Yuan 3) 4,001~6,000 Yuan

4) 6,001~10,000 Yuan 5) 10,000~15,000 Yuan 6) 15,001~30,000 Yuan

7) ≥30,001 Yuan

2. **Energy Consumption** (14 questions)

Overall Energy Consumption

2.1 What types of energy are used in your house? (click all that apply)

1) Electricity 2) Natural Gas 3) Liquefied Petroleum Gas

3) Biomass 4) Solar 5) Coal 6) Others____

2.2 Please record the last year energy use information (checking energy bills):

	Electricity		**Natural Gas (or LPG)**		**Other Energy Type**	
	kWh	Yuan	m^3	Yuan		Yuan
2011-01						
2011-02						
2011-03						
2011-04						
2011-05						
2011-06						
2011-07						
2011-08						
2011-09						
2011-10						
2011-11						
2011-12						
Total						

Space Cooling

2.3 How many rooms in your house have air conditioners installed? _______

Please fill in the output capacity and number of air conditioners in each room:

Room	**Cooling Capacity** (kW)	**Units**	**EE Tier** (EER or SEER)	**Type** Window (W) or Split (S) / FSAC (F) or VSAC (V)	**Purchase Year**
Living Room					
Master Bedroom					
Bedroom 1					
Bedroom 2					
Study Room					
Other Room					

2.4 The normal operation duration of the air conditioners in your house is:

From the (1. Beginning; 2. Middle; 3. End) of the month of __________;

To the (1. Beginning; 2. Middle; 3. End) of the month of ____________;

2.5 The use frequency of your air conditioners during cooling season is:

1) Not every day (only when needed) 2) Almost every day

2.6 The normal indoor setting temperature of your air conditioners is _____ ℃.

2.7 The use mode of your air conditioners in cooling season is:

I) About operating space:

1) Keeping occupants in one room and only turn on the air conditioner at that room;

2) Any room once it is occupied;

3) All rooms once there are people at home;

II) About turn-on/turn-off

1) Turn-on only when feel hot;

2) Turn-on once when people at home;

3) Keep running even no people at home;

III) About turn-on/turn-off when sleeping

1) Turn-off when go to sleep;

2) Turn-on while sleeping;

Water Heating

2.8 What equipment is/are used in your house for water heating?

1) Electric water heaters 2) Gas water heaters 3) Solar water heaters

4) Centralized hot water 5) Other____________

2.9 Shower frequency of family members (times per week)

Summer______; Winter________; Spring and Autumn_____;

2.10 If you do not have a solar water heater, but you ever thought about installing one, what are the reasons you did not install it?

1) Did not get a permission from the building management;

2) Building structure does not allow installation;

3) Too expensive;

4) Other ________________;

Household Appliances

2.11 The main cooking appliances in your house are:

1) Electric stoves 2) Gas stoves 3) Coal-related stoves

4) Biomass-related stoves 5) Others___

2.12 The frequency of your cooking:

1) Three meals per day 2) Two meals per day

3) One meal per day 4) Less than one meal per day

2.13 Please fill in the below table with the household appliances in your house.

(For certain appliances, if more than one unit are involved, please list the details for all of them)

Appliances	**Capacity** [1]	**Type** [2]	**EE Tier or Key Info. on EE Labels**[3]	**Amount** (units)[4]	**Use Frequency** (times per week & hours per time)[5]	**Purchase Year**
Refrigerator						
TVs						
Rice Cookers						
Clothes Washers						
PCs						
Microwave Ovens						
Irons						
Stereos						
Clothes Dryers						
Electric Water Heaters						
Gas Water Heaters						
Gas Cook Stoves						

Note: [1] The capacity for refrigerators is store volume (liters) and number of doors; for TVs is screen size (inches); for PCs is displayer size (inches); for clothes washers is maximum washing load (kg/cycle); for electric water heaters is water tank volume (liters); for gas water heaters is hot water output (liter/minute); for gas cook stoves is numbers of burners; for the other appliance is power capacity (w); [2] The types for TVs are CRT, CCFL, PDP, LED; for clothes washers are top-loading (T) and front-loading (F); for cook stoves are desktop (D) and built-in (B); for PCs are laptop and desktop; [3] The key information on energy efficiency labels for refrigerators is electricity consumption "kWh/24 hours"; [4] If more than one unit are owned by the households, please fill in the related information for each unit; [5] For certain appliances (like microwave ovens and water heaters), adopting the unit "minutes per time" rather than "hours per time" may be more appropriate (please clearly indicate the adopted units on the questionnaires).

Lighting

2.14 Please fill in the below table with the installed lighting fixtures in your house:

Room	**Amount of Rooms**	**Energy-Saving Lamps** (FLs, CFLs, LED, etc.)		**Incandescent Lamps**	
		Total Installed Wattage (w)	Use Time (hours/day)	Total Installed Wattage (w)	Use Time (hours/day)
Living Room					
Bedroom					
Study Room					
Dining Room					
Kitchen					
Bathroom					
Other Room					

3. <u>Awareness and Willingness to Energy Efficient Housing</u> (21 questions)

(This part is omitted here as it is not for the research purpose of this dissertation)

Appendix B

PROJECTION RESULTS OF RESIDENTIAL ENERGY CONSUMPTION IN XIAMEN

Table B-1 Projection of REC-BAU in Xiamen (FESL Scenario) (Unit: PJ)

Year	RE	AC	WM	TV	RC	PCM	EWH	OPA	Lighting	GWH	GS	H&S	Total
2011	2.270	3.624	0.360	1.192	1.076	0.132	2.149	1.877	1.338	0.043	11.160	0.433	25.656
2012	2.185	3.717	0.398	1.191	1.115	0.134	2.243	1.942	1.384	0.045	11.592	0.448	26.394
2013	2.120	3.716	0.437	1.215	1.155	0.136	2.340	2.010	1.432	0.046	12.039	0.464	27.111
2014	2.056	3.736	0.451	1.193	1.197	0.138	2.440	2.080	1.482	0.048	12.502	0.480	27.803
2015	1.993	3.758	0.466	1.172	1.240	0.140	2.543	2.152	1.534	0.050	12.837	0.497	28.383
2016	1.932	3.783	0.481	1.152	1.285	0.143	2.650	2.228	1.588	0.052	13.187	0.514	28.994
2017	1.872	3.811	0.497	1.133	1.331	0.145	2.760	2.306	1.643	0.053	13.553	0.532	29.637
2018	1.814	3.842	0.513	1.115	1.379	0.148	2.874	2.387	1.701	0.055	13.937	0.551	30.316
2019	1.757	3.876	0.530	1.099	1.429	0.151	2.991	2.471	1.761	0.057	14.337	0.570	31.029
2020	1.701	3.913	0.547	1.083	1.481	0.154	3.097	2.558	1.823	0.059	14.719	0.590	31.726

Note: RE, AC, WM, TV, RC, PCM, EWH, OPA, GWH, GS and H&S respectively stand for refrigerators, air conditioners, clothes washers, television sets, rice cookers, PC monitors, electric water heaters, other plug-in appliances, gas-fired water heaters, gas stoves, heat and solar for water heating.

(Source: Author’s calculation based on Equations 3.14-3.27)

Table B-2 Projection of REC-BAU in Xiamen (IESL Scenario) (Unit: PJ)

Year	RE	AC	WM	TV	RC	PCM	EWH	OPA	Lighting	GWH	GS	H&S	Total
2011	2.270	3.624	0.360	1.192	1.076	0.132	2.149	1.877	1.338	0.043	11.160	0.433	25.656
2012	2.383	4.045	0.434	1.299	1.216	0.146	2.446	2.119	1.384	0.049	11.592	0.489	27.602
2013	2.394	4.187	0.493	1.373	1.305	0.154	2.643	2.270	1.432	0.053	12.039	0.524	28.865
2014	2.404	4.355	0.554	1.395	1.400	0.161	2.853	2.432	1.482	0.056	12.502	0.561	30.157
2015	2.420	4.547	0.619	1.423	1.505	0.170	3.088	2.613	1.534	0.060	12.837	0.603	31.419
2016	2.435	4.749	0.686	1.452	1.619	0.180	3.339	2.807	1.588	0.065	13.187	0.648	32.754
2017	2.448	4.962	0.756	1.482	1.741	0.190	3.609	3.015	1.643	0.070	13.553	0.696	34.166
2018	2.461	5.189	0.829	1.513	1.872	0.201	3.899	3.239	1.701	0.075	13.937	0.747	35.664
2019	2.473	5.428	0.906	1.547	2.012	0.213	4.211	3.479	1.761	0.080	14.337	0.803	37.249
2020	2.485	5.684	0.985	1.582	2.163	0.225	4.523	3.737	1.823	0.086	14.719	0.862	38.876

Note: RE, AC, WM, TV, RC, PCM, EWH, OPA, GWH, GS and H&S respectively stand for refrigerators, air conditioners, clothes washers, television sets, rice cookers, PC monitors, electric water heaters, other plug-in appliances, gas-fired water heaters, gas stoves, heat and solar for water heating.

(Source: Author’s calculation based on Equations 3.14-3.27)

Table B-3 Projection of REC-BPI in Xiamen (FESL Scenario) (Unit: PJ)

Year	RE	AC	WM	TV	RC	PCM	EWH	OPA	Lighting	GWH	GS	H&S	Total
2011	2.270	3.624	0.360	1.192	1.076	0.132	2.149	1.877	1.338	0.043	11.160	0.433	25.656
2012	2.185	3.622	0.395	1.191	1.105	0.134	2.218	1.942	1.384	0.044	11.592	0.448	26.260
2013	2.100	3.544	0.430	1.191	1.135	0.136	2.290	2.010	1.432	0.046	12.039	0.464	26.816
2014	2.016	3.490	0.435	1.136	1.166	0.138	2.364	2.080	1.482	0.047	12.502	0.480	27.336
2015	1.933	3.439	0.441	1.081	1.199	0.140	2.442	2.152	1.534	0.048	12.649	0.497	27.554
2016	1.851	3.390	0.447	1.027	1.233	0.143	2.523	2.228	1.588	0.049	12.809	0.514	27.800
2017	1.770	3.343	0.453	0.974	1.268	0.145	2.606	2.306	1.643	0.051	12.983	0.532	28.074
2018	1.690	3.298	0.460	0.922	1.306	0.148	2.694	2.387	1.701	0.052	13.173	0.551	28.381
2019	1.611	3.256	0.467	0.870	1.345	0.151	2.784	2.471	1.761	0.053	13.377	0.570	28.718
2020	1.534	3.217	0.481	0.820	1.385	0.154	2.883	2.558	1.823	0.055	13.561	0.590	29.063

Note: RE, AC, WM, TV, RC, PCM, EWH, OPA, GWH, GS and H&S respectively stand for refrigerators, air conditioners, clothes washers, television sets, rice cookers, PC monitors, electric water heaters, other plug-in appliances, gas-fired water heaters, gas stoves, heat and solar for water heating.

(Source: Author's calculation based on Equations 3.14-3.26 and 3.28)

Table B-4 Projection of REC-BPI in Xiamen (IESL Scenario) (Unit: PJ)

Year	RE	AC	WM	TV	RC	PCM	EWH	OPA	Lighting	GWH	GS	H&S	Total
2011	2.270	3.624	0.360	1.192	1.076	0.132	2.149	1.877	1.338	0.043	11.160	0.433	25.656
2012	2.383	3.948	0.431	1.299	1.205	0.146	2.419	2.119	1.384	0.049	11.592	0.489	27.463
2013	2.371	4.000	0.486	1.345	1.282	0.154	2.586	2.270	1.432	0.051	12.039	0.524	28.541
2014	2.357	4.087	0.542	1.328	1.364	0.161	2.765	2.432	1.482	0.055	12.502	0.561	29.636
2015	2.346	4.189	0.602	1.312	1.455	0.170	2.965	2.613	1.534	0.058	12.649	0.603	30.496
2016	2.332	4.294	0.662	1.294	1.554	0.180	3.179	2.807	1.588	0.062	12.809	0.648	31.408
2017	2.314	4.402	0.725	1.274	1.659	0.190	3.409	3.015	1.643	0.066	12.983	0.696	32.375
2018	2.293	4.514	0.789	1.251	1.772	0.201	3.655	3.239	1.701	0.070	13.173	0.747	33.406
2019	2.268	4.631	0.855	1.225	1.893	0.213	3.920	3.479	1.761	0.075	13.377	0.803	34.500
2020	2.241	4.754	0.934	1.197	2.023	0.225	4.211	3.737	1.823	0.081	13.561	0.862	35.650

Note: RE, AC, WM, TV, RC, PCM, EWH, OPA, GWH, GS and H&S respectively stand for refrigerators, air conditioners, clothes washers, television sets, rice cookers, PC monitors, electric water heaters, other plug-in appliances, gas-fired water heaters, gas stoves, heat and solar for water heating.

(Source: Author's calculation based on Equations 3.14-3.26 and 3.28)