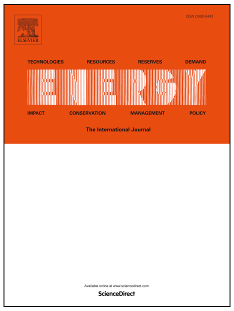

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Static analysis of technical and economic energy-saving potential in the residential sector of Xiamen city

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Abstract

Based on a household energy use survey, this paper explores the technical and economic potential of residential energy savings in a Chinese city, Xiamen. The survey adopted a similar questionnaire used by the U.S. EIA's Residential Energy Consumption Survey (RECS), covering the end-uses of cooking, water heating, plug-in appliances, lighting and space cooling. The analysis shows that the technical potential of energy savings in Xiamen's residential buildings is significant, around 20%. Of the technical potential, about two-thirds to four-fifths are cost-effective from a whole society perspective. The cost-effectiveness was evaluated by comparing the Levelised Cost of Conserved Energy (LCOCE) of advanced technical measures with the actual cost of conserved energy. The actual cost of energy is defined by adding the carbon emission cost and hidden government subsidies over the retail prices of energy. About three-quarters of the technical energy-saving potential in Xiamen come from adopting efficient household appliances, therefore, further tightening the energy efficiency standards for key household appliances and promoting wide diffusion of efficient models of appliances by various

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effective financial incentives are essential for achieving residential energy savings in China's "Hot Summer and Warm Winter" region where Xiamen locates.

Keywords: technical potential, economic potential, energy savings, household energy consumption, levelised cost of conserved energy, residential buildings

1. Introduction

Being the largest carbon emitter in the world, China's CO_2 emissions closely relate to its energy consumption. This is mainly because of China's heavy dependence on the use of coal, about 70% in primary energy consumption [1]. Both China's total primary energy use and CO_2 emissions have been significantly increased from their 1990 levels, about six and four times respectively [2]. Although the deployment of nuclear, hydro, geothermal, solar and wind energy has been increasing very fast in the nation, they together still account only for a tiny share (around 5%) in China's primary energy supply [3]. Therefore, improving energy efficiency will remain crucial in the long run for China's commitments to climate change mitigation.

The residential building sector in China accounts for a significant share (approximate to 25%) of the nation's total final energy consumption [3]. In addition, owing to fast improvements of people's quality of life, the residential energy consumption intensity (per capita) in China has been increasing (see Figure 1). It increased by about 21% from 2005 to 2014, in sharp contrast with the significant drop of about 46% in China's industrial energy intensity (per 1000 Chinese Yuan industrial GDP) during the same period [1,3,4,5].

Given China's continuous economic growth and fast urbanization, its residential energy consumption and related CO_2 emissions are expected to have a substantial increase in the foreseeable future with the business-as-usual scenario. Promoting energy efficiency and conservation in China's residential building sector is, therefore, urgent. To address this issue, a fundamental step is to analyze the energy-saving potential in Chinese residential buildings.

Much research has been done on energy-saving potential analysis in buildings. However, the adopted analytical approaches vary among studies. In the research [6-11], the potentials were estimated based on the efficiency difference between existing technical measures in the building stock and anticipated advanced measures in the market. The studies [12-14] focused on the cost-effectiveness of energy-saving potential, while Broin et al. calculated the potential by assuming policy scenarios first [15].

Nonetheless, the U.S. Environmental Protection Agency's "2007 Guide for Conducting Energy Efficiency Potential Studies" (hereafter referred to as the 2007 EPA Guide) suggests a conceptual framework of standard approaches for energy-saving potential analysis [16]. This framework could well cover the existing potential analysis approaches. By taking the view of efficiency as the supply-side alternative, the 2007 EPA Guide divided the energy-saving potential coming from energy efficiency improvements into four categories: technical, economic, achievable, and program potential.

In the 2007 EPA Guide, 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 as the "subset of the technical potential that is economically cost-effective as compared to conventional supply-side energy resources" [16].

Both the EPA's definitions of technical and economic potential assume "complete" and "immediate" replacement of existing technical measures by advanced ones, and they are, therefore, static potential analysis. In contrast, the achievable and program potential analyses involve a dynamic calculation process as they need to consider the real-world gradual adoption process of advanced technical measures (i.e., additions and replacements) within a certain time horizon as well as to take into account consumers' choices of efficiency-different appliances.

Different potential analysis serves different policymaking needs, and adopts different analytical approaches [16]. Static technical and economic potential studies target to help policymakers to design general energy policies for a sector. In comparison, dynamic achievable and program potential research is for assessing the impact of specific incentives on energy savings within a sector.

Using Xiamen city in China as a case study, this paper explores static technical and economic energy-saving potentials in Chinese urban residential buildings[2]. The analysis in this paper is based on a household energy use survey conducted in Xiamen in 2012, which adopted the same survey methods used by the U.S. Energy Information Administration's Residential Energy Consumption Survey (RECS) [17].

Xiamen lies in southern China's Fujian province, belonging to the "hot summer and warm winter (HSWW)" climate zone according to the nation's classification in energy performance design of buildings. Owing to its warm climate (all-year-round average temperature of 21°C) [18], space heating in the city is not needed. Hence, our surveyed household energy consumption in Xiamen includes the end-uses of lighting, cooking, water heating, plug-in appliances and space cooling.

Space heating is needed in northern China where district (or centralized) systems are dominant. These district systems widely lack household controlling measures. Consequently, the space heating energy consumption in China is usually out of the control of households themselves.

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[2] The analysis of dynamic achievable and program residential energy-saving potentials in Xiamen city was presented in another paper [https://doi.org/10.1016/j.rser.2016.04.070]. These two papers adopt completely different analytical approaches suggested by the EPA [16], although they partly share the common data from our household energy use survey in Xiamen city.

Therefore, by studying Xiamen's household energy consumption, this paper principally focuses on the part of energy consumption in Chinese urban residential sector that can be substantially influenced by the household's own lifestyles or occupant behaviors. In fact, as the use patterns for the end-uses of lighting, cooking, water heating, plug-in appliances and space cooling do not vary much among Chinese cities [19], the Xiamen case can represent to some extent the residential energy consumption excluding space heating in northern Chinese cities as well.

In addition, being one of the most developed cities in China (with a per capita GDP of about 1.8 times the national average) [1, 18], the overall efficiency levels of household appliances in Xiamen are relatively higher than the Chinese average. Therefore, exploring the residential energy-saving potential in Xiamen can be seen as a conservative (or "safe") choice for estimating the scale of potential in the nation.

2. Methodology

2.1 Analysis method for technical potential

According to the definition of technical potential given by the 2007 EPA Guide as well as referring to Swisher et al. [16, 20], the general calculation principles of technical potential can be expressed as follows:

$$EEG_i = f\left(EE_{(i,new\_h)}, EE_{(i,cur)}\right) \qquad (1)$$

$$ESP_i = OS_i \times UEC_{(i,cur)} \times EEG_i \qquad (2)$$

$$ESP = \sum_{i=1}^{n} ESP_i / \sum_{i=1}^{n} [OS_i \times UEC_{(i,cur)}] \qquad (3)$$

where the subscript "*i*" denotes a certain type of household energy end-use equipment; "EEG_i" stands for the energy efficiency gap between the most efficient alternative available in the market

"$EE_{(i, new\_h)}$" and the existing stock "$EE_{(i, cur)}$", which is expressed in the form of reduction percentage in energy use from the current energy consumption level (it is worth noting that the *EEG* calculation varies for household equipment, and also closely relates to selected energy efficiency indicators); "OS_i" represents the average ownership of equipment "*i*" (units per household); "$UEC_{(i, cur)}$" indicators the "Unit Energy Consumption (UEC)" of the existing stock of equipment "*i*" (MJ/unit·year) - the concept and calculation of UEC for various household equipment can refer to the NREL [21] and the EIA [22]; "ESP_i" stands for the energy savings (MJ/year) achieved from adopting the efficiency-highest alternative (or measure) for equipment "*i*"; "*n*" denotes the total number of involved energy end-use equipment; "*ESP*" is the total technical potential of energy savings (expressed in the form of a reduction percentage from the current energy consumption).

Equation 1-3 present only the general calculation principles for technical potential. In practice, such a calculation is often complex for several reasons, First, the selection of feasible technical measures should be closely based on a comprehensive analysis of current residential energy use pattern, which is often difficult to be obtained in developing countries because of the availability of household energy use survey data (e.g., no RECS in China yet). Second, the efficiency indicators of feasible technical measures vary, and their selection is often restricted by existing energy efficiency policies. For example, whether or not there exist energy efficiency standard and labeling (EES&L) schemes for household appliances. Third, the "interlinked impacts" of different technical measures need to be considered, such as the impact of retrofitting building envelopes on the cooling load of room air conditioners. Last, there are uncertainties with regard to the "replacement effects" among different types of certain appliances. As an example, there are two basic types of washing machines in the Chinese market, top-loading type and front-loading type. The two types have quite differences in energy efficiency [23], and each accounts for a significant stock share in Chinese households. Thus, to calculate the technical potential obtained from washing machines the “replacement effects” between the two types must be taken into account.

As shown in Equation 1-3, the main data required for technical potential calculation are four: “OS_i”, “$UEC_{(i, cur)}$”, “$EE_{(i, cur)}$”, and $EE_{(i, new\_h)}$”. Of them, the first three mean knowing the household energy use pattern that can be obtained from a designed household energy use survey, while the last one can be collected from a market survey.

2.2 Analysis method for economic potential

As mentioned in Section 1, economic potential refers to the aggregated technical potential 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 with different energy efficiency available in the market for a certain appliance. China’s EES&L schemes for household appliances usually adopt three or five tiers of efficiency [23]. Among these efficiency-different options, the one with higher efficiency is usually more expensive. Therefore, the equipment with the lowest-efficiency available in the market can be viewed as consumers’ baseline (or reference) option for replacing the existing one, while the others are superior options. Between the baseline option and each superior option, two gasps exist: an energy efficiency gap and a cost gap (also called incremental cost) [19, 24-25].

According to the ACEEE [24], the cost-effectiveness of a technical measure is determined by if its “Levelised Cost of Conserved Energy (LCOCE)” is less than the average retail price of energy. This paper focuses on the significance of improving residential energy efficiency in the nation, therefore, a whole society perspective is taken in the economic potential analysis. From a whole society perspective, the technical measures that can contribute to the "economic potential" of energy-savings can be screened by comparing their LCOCE with the actual social cost of conserved energy. The judgment rule can be presented as follows [24]:

$$LCOCE\ (TM_i) \leq AC_{energy} \qquad (4)$$

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

According to the NREL [21], the LCOCE of an advanced energy-saving measure can be calculated as follows:

$$LCOCE(TM_i) = \frac{\boldsymbol{IC_{(i,0)}} + \sum_{t=1}^{n} \frac{\boldsymbol{OC_{(i,t)}}}{(1+d)^t}}{\sum_{t=1}^{n} \frac{\boldsymbol{CE_{(i,t)}}}{(1+d)^t}} \qquad (5)$$

where "t" represents the lifetime of the advanced measure "i" ("$t=1$" and "$t=n$" then respectively mean *"the first year"* and *"the last year"* of the measure's lifetime); "$IC_{(i,0)}$" stands for the incremental upfront cost of the measure "i"; "$OC_{(i,t)}$" represents the incremental operation cost in the year "t" ;"$CE_{(i,\ t)}$" means the conserved energy in the year "t" caused by adopting the measure "i";"d" is the discount rate.

The energy used in Chinese urban residential buildings is basically two types: electricity and natural gas (or liquefied petroleum gas instead) [19], therefore, the "AC_{energy}" in Equation 4 mainly means the actual social cost of electricity or natural gas for urban Chinese households. In China, the retail price of electricity (or natural gas) for households is subsidized directly and indirectly in many forms by the governments (e.g., tax benefits, less cost of land use for utility companies), and is intentionally underrated from its actual cost because of certain concerns (e.g., as social welfare to households) [26-27]. In addition, the environmental externalities of energy production and consumption is usually not considered in energy pricing in China. Therefore, in order to better evaluate the economic potential of energy-savings from a whole society perspective, the actual social cost of energy in China needs to be measured at least by including three components, retail price (“RP_{energy}”), government subsidies (“GS_{energy}”) and externality cost (“EX_{energy}”) (electricity: “Yuan/kWh”; natural gas: “Yuan/MJ”), shown as follows:

$$AC_{energy} = RP_{energy} + GS_{energy} + EX_{energy} \qquad (6)$$

A comprehensive evaluation of the negative environmental effects of energy consumption is challenging, and beyond the scope of this research. In this paper, the externality cost of energy use in China only includes related carbon emission cost considering the existing domestic carbon trading market. This will underestimate the economic potential to some extent as the emission costs of other air pollutants (e.g., SOx, NOx and PM2.5) and their negative health effects are not covered.

Once all the cost-effective technical measures are identified based on Equation 4-6, the economic potential of residential energy savings can be calculated through Equation 1-3 by substituting cost-effective measures into them.

3 Data collection

3.1 Household energy use survey in Xiamen

The survey questionnaire was modified from the one used by the US EIA's RECS. A total of 150 randomly selected households in the city were surveyed for their energy use patterns in the year of 2011. These households are geographically dispersed in thirty-five sub-districts in Xiamen's four core municipal districts (Hu Li, Si Ming, Ji Mei and Tong An). The four core districts accommodate about 80% of Xiamen's population [18]. There are in total 350 sub-districts in the city [18], thus our survey covered one-tenth of them. Such a wide distribution of households in geographic locations ensures the representativeness of our survey samples, which can be further observed from the distribution of our surveyed households in several key features, such as housing floor space, building's age, household size, age of occupants, household income, and education level of occupants (see Figure 2).

Figure 2 shows that the distribution of our survey samples are quite diversified in four of these key features, namely housing floor space, age of occupants, household income, and education level of occupants. As for the building's age, about 87% of our surveyed households lived in buildings constructed after 1990. This distribution well reflects the reality in Xiamen city. According to the Xiamen Bureau of Statistics (XBS) [28], it was estimated that about 90% of the city's existing residential buildings were constructed after 1990. In addition, the XBS reported that the share of Xiamen households that comprise only 1-2 persons is about 54% [29]. Our survey samples are rather consistent with this fact. Of the total 150 surveyed households, 110 of them are home owners and the rest are tenants, which also accords with the current situation in most Chinese cities, namely around 30% of housing units occupied by tenants [19].

To further check the representativeness of the survey samples, the housing pattern of our surveyed Xiamen households is summarized in Table 1, along with showing a comparison with related statistical data from the XBS [30]. The housing pattern of our survey samples and that represented by the XBS statistics are rather in line with each other. In short, our survey samples are fair representation of the overall household structure in the city of Xiamen.

Based on our household energy use survey conducted in Xiamen, the average household energy use pattern in the city was mapped (see Figure S-1 in Supplementary Information). The residential energy intensity in Xiamen on average is about 208 MJ/m^2.year (or 8,463MJ/capita.year). Cooking, with a share of about 42%, is the largest energy end-use in Xiamen households. Plug-in appliances, space cooling and water heating are the following end-uses, with a share of 25.6%, 13.7% and 13.7% respectively. As over 80% of the households in Xiamen have adopted efficient lamps, such as compact fluorescent lamps (CFLs) and light-emitting diode (LED) lamps, lighting consumes the least energy, about 5%. In this sense, the energy-saving potential from lighting in Xiamen households may be insignificant.

In order to examine the reliability of our mapped Xiamen household energy use pattern, a cross-check on the household electricity consumption intensity (HECI) between our survey and the XBS statistics was conducted[3]. From our micro-level household survey, the HECI is approximately the total of intensity of lighting, plug-in appliances, space cooling and electric water heating, which was about 31.6 kWh/$m^2 \cdot$ year in 2011. The XBS statistics showed that the 2011 HECI in Xiamen was about 33.96 kWh/$m^2 \cdot$ year [30], which was calculated from dividing the macro-level total household electricity use in Xiamen by the city's total floor space of residential buildings. The two HECIs are in quite accordance with each other, with a difference of only about 7.5%. This cross-check provides additional confidence in the representativeness and reliability of our survey data.

3.2 Market survey

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[3] No household gas consumption data available in Xiamen's Statistical Yearbooks.

Conducting technical and economic potential analyses needs to know efficient options of various appliances available in the market and related incremental costs. Such information can be attained from a market survey. For this study, this was mainly done by collecting related data on the website of SUNING[4], which is one of the largest online dealers of household appliances in China.

The energy efficiency indicators for most household appliances in China have been stipulated in related mandatory national EES&L schemes, and presented on the energy labels of appliances [23]. The schemes categorize energy efficiency into 3 or 5 tiers. The Tier-1 represents the highest efficiency of appliances available in the Chinese market.

From the market survey, the currently implemented energy efficiency indicators and Tier-1 efficiencies for main household appliances in the Chinese market are summarized (see Table S-1 in Supplementary Information). The efficiency levels and capacity factures of existing appliances in Xiamen's households are also presented in that table, which were collected through our Xiamen household energy use survey.

It is worth noting that the selected efficiency indicator for refrigerators is not the one stipulated in related national EES&L scheme (i.e., GB12021.2-2008). In that scheme, the efficiency indicator for refrigerators is expressed as a virtual parameter of "η" that represents a percentage to an assumed energy use level, which is not applicable for the potential analysis. Therefore, the indicator of "daily electricity use" of refrigerators is used in this paper instead, which is printed on the mandatory energy label of refrigerators. By surveying the product information on the SUNING website, it was found that the typical refrigerators in Xiamen households (i.e., 151-230 litre volume) could be generally divided into two distinct groups in terms of "daily electricity

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[4] http://www.suning.com

use”, namely one baseline group with electricity use about 0.47-0.49 kWh/day, and one advanced group with about 0.37-0.39 kWh/day.

The market survey also showed that some household appliances in China have two basic types that have significant difference in energy efficiency. These include room air conditioners (fixed-speed and variable-speed), washing machines (top-loading and front-loading), and gas cook stoves (built-in and desktop). Each basic type of the three appliances accounts for a significant stock share in Xiamen households. For washing machines and gas cook stoves, the energy efficiency indicator are the same for their basic types. However, the efficiency indicators for the two types of room air conditioner are different and not comparable directly. The fixed-speed air conditioners (FSAC) use “Energy Efficiency Ratio (EER)” as the indicator which denotes the ratio of output cooling energy to input electrical energy, while for variable-speed air conditioners (VSAC) the indicator is “Seasonal Energy Efficiency Ratio (SEER)” defined as total cooling output divided by total electric energy input during a typical cooling season. According to Xu & Liao [31], the EER of FSACs would increase by about 0.6 (0.57-0.64) when adopting the SEER testing method. To make the EER and SEER comparable in energy-saving potential analysis, such an efficiency correction for room air conditioners is conducted in this paper.

In addition, from the market survey the incremental purchase costs of efficient appliances were also collected (see Table S-2 in Supplementary Information). It is worth noting that for some household appliances such as TVs, rice cookers and electric water heaters, there is no significant price increase corresponding to the improvement of efficiency. This means that these appliances’ prices are clearly driven by other product attributes (e.g., functionality, brand and design), but not energy efficiency.

3.3 Discount rate

In Equation 5, a discount rate is required for calculating the Levelised Cost of Conserved Energy (LCOCE). According to the NAPEE [32], three perspectives are often taken for evaluating energy efficiency improvement projects, and each adopts different kind of discount rate (see Table 2). As mentioned before, this paper takes a whole society perspective to conduct the economic potential analysis, therefore, a social discount rate is used for the LCOCE calculation.

The Asian Development Bank (ADB) summarized the social discount rates utilized in certain countries (within a broad range from 3% to 15%) [33]. It reported that the widely-used social discount rate in China is 8%. A higher social discount rate of 10% for China was adopted in the model of Policy Analysis Modeling System (PAMS) [34]. The PAMS model is co-developed by the CLASP and the U.S. Lawrence Berkeley National Laboratory (LBNL) for evaluating the benefits of appliance EES&L schemes. In this paper, a social discount rate of 8% is used as the reference rate, while the rates of 6% and 10% are also adopted for a sensitivity analysis.

3.4 Lifetime of technical measures

The typical lifetime of household appliances in China were stipulated in the national standard "Safety Use Lifetime of Household Appliances" [35]. The lifetime of gas water heaters was stated in another national standard "GB 17905-2008" [36], suggested to be eight years. A summary of appliance lifetimes is shown in Table 3. For residential building envelopes in China, the lifetime are usually viewed to be 20-25 years [37].

3.5 Actual cost of energy in Xiamen

Our Xiamen survey showed that the average household electricity consumption in the city was about 2,963kWh/year. According to the current multistep electricity pricing scheme in Xiamen, the weighted average electricity price for Xiamen households is about 0.5078 Yuan/kWh. The trading price of carbon emissions in China in June 2017 was about 46.6 Yuan/ton according the Beijing Environment Exchange [38]. Given China's carbon emission coefficient of electricity generation of about 790 grams/kWh, and the average electricity transmission and distribution loss rate of 6.64 % in 2015 [39-40], it is estimated that the carbon emissions coefficient of electricity consumption in China is about 846 grams per kWh. Accordingly, the environmental externality cost of carbon emissions of electricity consumption in China is roughly about 0.0394 Yuan/kWh.

The current price of natural gas for Xiamen households is about 4.0 Yuan/m^3. According to the EPA [41], the carbon emissions factor of natural gas is about 53.06 kg/MBTU, which is equal to about 1.9 kilogram carbon emissions per cubic meter natural gas use in Xiamen. This implies that the carbon emission cost of natural gas consumption in Xiamen is about 0.1047 Yuan/m^3.

Both electricity and natural gas in China are subsidized in various forms by the governments (e.g., tax benefits, less cost of land use by utility companies), which makes their retail prices lower than what they should be. It was estimated that the subsidies for the residential sector might be about 0.54 Yuan/kWh for electricity and 1.26 Yuan/m^3 for natural gas [27].

Based on the above information, the actual social cost of electricity and natural gas for Xiamen households should be, at least, about 1.0872 Yuan/kWh for electricity and 5.3647 Yuan/m^3 for natural gas.

4 Analysis results

4.1 Technical potential

Based on our Xiamen household energy use survey, we picked several significant technical measures for achieving residential energy savings in the city (see Table 4). The end-use of lighting is not involved because of its very limited potential contribution. As for plug-in appliances, this research particularly focuses on four main appliances (i.e., refrigerators, TVs, rice cookers and washing machines), as they together consume about 70% of the total electricity use by plug-in appliances in Xiamen households (see Figure S-1 in Supplementary Information).

For space cooling energy consumption in Xiamen, the interlinked effects of two types of technical measures have to be considered: retrofitting building envelopes and adopting efficient room air conditioners. Cai [42] reported that retrofitting walls, roofs and windows in Xiamen's residential buildings could contribute to a reduction of a building's cooling load by about 2.5%, 8.8% and 32.0% respectively from the existing level. The existing popular envelopes of Xiamen's residential buildings were those constructed during the 1990s and 2000s (accounting for almost 90% of the residential building stock in the city), while the adopted envelope retrofitting measures are in compliance with the latest building energy code, JGJ75-2012, for China's "Hot Summer and Warm Winter" region where Xiamen locates.

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 the city could significantly impede the natural indoor-outdoor heat transfer through walls during nighttime, and 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 [19], which explains why retrofitting roofs and windows are relatively much more effective. Accordingly, in this paper upgrading the roofs and windows of buildings is selected as an appropriate and significant technical measure for retrofits in Xiamen's residential buildings. The related incremental costs are about 6 Yuan/m^2 and 85 Yuan/m^2 for upgrading roofs and windows respectively[5] [43].

Based on Equation 1-3, the technical potential of electricity saving in Xiamen's residential buildings were calculated (see Table 5). Such a potential is about 33.98 MJ/m^2· year, meaning a reduction percentage of about 29.9% from the 2011 baseline level (113.7 MJ/m^2· year).

It must be noted that the "replacement effects" among different types of certain appliances are not considered in the calculation of Table 5. Such replacement could have a significant impact on the scale of technical potential given the efficiency difference among different types of these appliances. According to our market survey, there are currently two possible trends of appliance type replacements for electricity consumption in Xiamen households: 1) VSACs replacing FSACs; and 2) front-loading wash machines replacing top-loading ones. Table 6 shows the replacement impacts on the electricity savings in Xiamen households. In Table 6, Scenario-I does not consider the replacement between different types of room air conditioners or washing machines (e.g., Tier-1 VSACs replace only current VSACs and Tier-1 FSACs replace only current FSACs), while Scenario-II considers such replacement effects (e.g., Tier-1 VSACs replace both current VSACs and FSACs). Therefore, the changes in electricity consumption intensity between the two scenarios represent the impact of appliance type's "replacement effects" on the electricity-saving technical potential in Xiamen households.

If the replacement between appliance types 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 of electricity savings in Xiamen

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[5] The square meter here means the floor space of buildings but not the area of roofs or windows.

households, in the form of a reduction percentage from the 2011 baseline level, may vary in the rage of 26.4% to 32.3%.

Similarly, the calculation results for the technical potential of natural gas savings are presented in Table 7. Such a potential is about 14.84 MJ/m^2· year, meaning a reduction percentage of about 16.3% from the 2011 level. There is also a “replacement effect” for natural gas consumption, namely built-in type gas cook stoves replacing desktop type ones. When considering that, the natural gas consumption intensity in Xiamen households might increase by about 1.45 MJ/m^2· year, implying a drop of gas-saving technical potential from 16.3% to about 14.7%.

In summary, the technical potential of energy savings in Xiamen’s residential buildings is rather significant, ranging from 26.4%-32.3% for electricity savings, and 14.7%-16.3% for natural gas savings, given the uncertainties of “replacement effects” among different types of certain appliances. When combining electricity and natural gas, the overall residential energy-saving technical potential in Xiamen will be within the rage of about 20.9% to 24.9%.

Figure 3 summarizes the contribution of various measures to the potential. It shows that adopting efficient gas cook stoves, use of efficient refrigerators, and retrofitting building envelopes (roofs and windows) are the top three critical measures. They together account for approximate 80% of the estimated technical energy-saving potential in Xiamen’s residential buildings.

4.2 Economic potential

As shown in Equation 4-6, the economic potential analysis is based on incremental costs of efficient technical measures. Our market survey found that the efficient 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.

As shown in Table S-2 in Supplementary Information, the first category includes the appliances of TVs, rice cookers and electric water heaters in the Chinese market. There are two main reasons why the incremental costs for these appliances (with the same capacity features) are not significant: 1) the efficiency improvement costs of these appliances are negligible; and 2) although such costs might not be insignificant, they are not correctly reflected in the appliances' pricing, that is, the pricing of these appliances is dominated by the products' other attributes rather than their energy efficiency. As no incremental cost is involved in adopting efficient models of these appliances, the technical potential contributed by them could be viewed as economic potential as well. According to Table 5, these three measures together (i.e., TVs, rice cookers and electric water heaters) could contribute to the reduction of electricity consumption in Xiamen's residential buildings by about 6.21 MJ/m^2· year.

For the other category of appliances, the LCOCE of adopting their efficient models can be calculated based on Equation 5 (see Table 8). The calculation reveals that there are three additional measures that can be viewed as cost-effective for residential energy savings in Xiamen by compared the calculated LCOCE with the actual social cost of electricity and natural gas in the city (i.e., 1.0872 Yuan/kWh for electricity and 5.3647 Yuan/m^3 for natural gas). The three measures are: 1) retrofitting roofs of buildings; 2) adopting efficiency-advanced refrigerators; and 3) adopting Tier-1 gas cook stoves.

In summary, there are in total six cost-effective measures for energy savings in Xiamen's residential buildings (see Table 9). From Table 9, given the 2011 electricity consumption intensity in Xiamen households (113.7 MJ/m^2· year), the economic potential of electricity savings would be about 18.3%. On the other hand, considering the 2011 residential natural gas consumption intensity of 90.9 $MJ/m^2 \cdot$ year in Xiamen, the economic potential of natural gas savings would range from 14.4-16.0%. In comparison with related technical potentials of electricity and natural gas, this means that about 56-69% of the electricity-saving technical potential and almost all (about 98%) the natural gas saving technical potential in Xiamen's residential buildings can be viewed as cost-effective from a whole society perspective.

4.3 Amendment of energy-saving potential

As there is no any further household energy use survey in Xiamen available after 2012, the technical energy-saving potential analysis in this paper has to be based on the data of a 2012 survey. Along with the gradual ramping-up process of efficient appliances into the household appliances stock (i.e., purchased by consumers for "additions" and replacing "retirements" of appliances), the average energy efficiency levels of appliances stock in Xiamen's households in the latest year (i.e., 2016) must be higher to some extent than those shown in Table S-1 in Supplementary Information. This implies that we may overestimate the technical potential in Xiamen households to some extent.

To address this issue, based on a projection of housing appliances stock in the city of Xiamen from 2010 to 2020 and a Kastovich-type consumer choice model [44, 45], we calculate the weighted average energy efficiency levels of the stock of involved appliances in 2016. By comparing the two sets of average efficiency levels of appliances (i.e., 2011 and 2016), we are able to attain the reduced energy savings when using the year of 2016 as the base year instead of the previous base year of 2011 (see Table 10).

Based on the data in Table 10, we can calculate that for a base year of 2016, the technical potential of residential electricity savings in the city may be about 24.6% (in comparison with the calculated 29.9% for a base year of 2011). The estimated technical potential of gas savings is about 13.7% (in comparison with the 16.3% for a base year of 2011). Combining electricity and gas together, the overall technical potential is about 19.4% for a base year of 2016 (in comparison with the 23.5% for a base year of 2011). Therefore, using the 2011 survey data we may roughly overestimate the technical potential of residential energy savings in Xiamen city by about 20%.

5. Concluding remarks

This paper explored the technical and economic energy-saving potentials in Chinese urban residential buildings, by using Xiamen city as a case study. Our study focuses primarily on the part of household energy consumption that can be substantially influenced by households' own lifestyles or occupants' behaviors, namely the end-uses of lighting, cooking, plug-in appliances, water heating and space cooling.

A household energy use survey was conducted in Xiamen, and it adopted a similar questionnaire used by the U.S. EIA's Residential Energy Consumption Survey (RECS). Based on the survey, the household energy use pattern in the city was mapped. It shows that cooking (42% of household energy use) is the largest end-use in Xiamen households, followed by plug-in appliances (25.6%), space cooling (13.7%), water heating (13.7%) and lighting (5%). As most Xiamen households (over 80%) have already completely adopted efficient lighting lamps such as CFLs and LED lamps, there is a limited energy-saving potential left for domestic lighting in the city.

The survey also revealed appropriate and significant technical measures for achieving residential energy savings in Xiamen. By implementing these measures, our analysis discovers that the technical energy-saving potential in Xiamen's residential buildings is currently rather significant, around 20%. Adopting efficient gas cook stoves, use of efficient refrigerators and retrofitting buildings' envelopes (particularly roofs and windows) are the top three critical measures. They together could account for approximate 80% of the existing technical potential. These three measures should, therefore, become the focus of energy-saving policymaking by the governments for this region (i.e., the "Hot Summer and Warm Winter" region). This also implies that any policy for energy savings in buildings must embrace local conditions, and should not be just simply transplanted from other countries or regions that have quite different household energy use patterns.

Of the technical potential, about two-thirds to four-fifths are cost-effective from a whole society perspective. The cost-effectiveness is evaluated by comparing the Levelised Cost of Conserved Energy (LCOCE) of advanced technical measures available in the market with the actual social cost of conserved energy. The actual social cost of energy in this paper is defined by adding the carbon emission cost and the hidden government subsidies over the retail prices of energy.

It is worth noting that for the electricity-saving measures, except for the only two cost-effective measures (i.e., retrofitting roofs of buildings and adopting efficient refrigerators), the LCOCE of all the other measures are about 3-13 times the actual cost of electricity in Xiamen. This indicates that most efficient household appliances currently available in the Chinese market are financially unattractive to the households mainly owing to the relatively low household electricity price and the significant incremental costs of such appliances. Therefore, giving the current price and efficiency spectrum of main household appliances in the Chinese market, providing consumers a certain amount of subsidies for purchasing efficient appliances could result in lower LCOCE of these appliances, and consequently facilitate the wider diffusion of them in Chinese households.

Controlling and reducing energy consumption in Chinese residential buildings is quite urgent as China's residential energy intensity is increasing rapidly. The window-of-opportunity that remains for taking serious efforts is very limited. As an example, the average household electricity consumption intensity (HECI) in Xiamen's U.S. counterparts (the areas with similar climate of Xiamen) was about 94.3kWh/m^2· year [17, 46]. This number is about three times Xiamen's 2011 level. Given the current average annual increase rate of HECI in Xiamen (about 6.5% from 2010 to 2015), if no strong policy intervention is introduced, Xiamen's HECI may reach its U.S. counterparts' level by 2030. If this scenario is allowed to be realized, the residential building sector will contribute significantly to the air pollutions and carbon emissions in the nation, considering China's heavy dependence on coal power generation in the long run.

In China's 13th Five Year Plan (2016-2020), the Chinese central government has set a cap for annual coal consumption of 5 billion tonne of coal equivalent (TCE) [47]. To achieve this overarching goal from the residential sector, the government plans to: 1) improve the energy performance of new buildings by 20% from the 2015 level by 2020; 2) retrofit 500 million square meters of existing residential buildings by 2020; and 3) promote the share of energy-saving buildings (i.e., the ones meeting building codes) to total existing buildings from 40% in 2015 to 60% in 2020 [48]. All these tasks primarily focus on improving energy performance of building envelopes, and this is very important for northern China as space heating there accounts for around half of household final energy use.

However, in southern China, especially in the "Hot Summer and Warm Winter" region where Xiamen locates, our analysis shows that about three-quarters of the technical energy-saving potential come from adopting efficient household appliances. Therefore, further tightening the energy efficiency standards for key household appliances and promoting wide diffusion of efficient models of appliances by effective financial incentives are essential for achieving residential energy savings in this region.

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Table 1: A comparison of housing pattern in Xiamen between our survey and the XBS statistics [30]

Housing pattern	**Sources**	
	Our Survey	XBS Statistics
Low or high rise apartments (%)	95.9	96.3
Attached or detached houses (%)	0.7	1.0
Others (e.g. simple self-built bungalow) (%)	3.4	2.7

Table 2: Discount rates for evaluating energy efficiency improvement projects [32]

Perspectives	**Discount rates**	**Details**
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

Table 3: Typical lifetime of household appliances and building envelopes in China [35-36]

Appliances or measures	Typical lifetime
Room air conditioners	8-10 years
Refrigerators	12-16 years
TVs	8-10 years
Rice cookers	10 years
Washing machines	8 years
Electric water heaters	8 years
Gas water Heaters	8 years
Gas cook stoves	8 years

Table 4: Selected significant energy-saving measures for Xiamen households

End-uses	Selected technical measures
Space cooling	Retrofitting building envelopes to reduce space cooling load
	Adopting efficient room air conditioners
Plug-in appliances	Adopting efficient refrigerators
	Adopting efficient TVs
	Adopting efficient rice cookers
	Adopting efficient washing machines
Water heating	Adopting efficient electric water heaters
	Adopting efficient gas water heaters
Cooking	Adopting efficient gas cook stoves

Table 5: Technical potential of electricity savings in Xiamen households

Measures	Electricity savings ($MJ/m^2\cdot year$)	Baseline energy consumption ($MJ/m^2\cdot year$)
Building envelope retrofitting[a]	11.63	28.5
Tier-1 room air conditioners	3.00[b]	
Efficiency-advanced refrigerators[c]	12.13	17.8
Tier-1 rice cookers	0.51	8.5
Tier-1 TVs	4.97	8.2
Tier-1 washing machines	1.01	2.8
Tier-1 electric water heaters	0.73	21.5
Total	33.98	n/a

Note: [a] the envelope retrofitting includes roof insulation and adoption of high-performance windows; [b] energy savings from room air conditioners are after building envelope retrofits; [c] efficiency-advanced refrigerators mean the ones consuming electricity about 0.38 kWh/day.

Table 6: Replacement effects of appliance types on the technical potential of residential electricity savings in Xiamen

Appliances	Replacement scenarios		Electricity consumption intensities ($MJ/m^2\cdot year$)		
	Scenario-I	Scenario-II	Scenario-I	Scenario-II	Changes
Room air conditions[a]	Tier-1 FSAC + Tier-1 VSAC	Only Tier-1 VSAC	14.2	11.4	-2.8
Washing machines	Tier-1 Top-loading + Tier-1 Front-loading	Only Tier-1 Front-loading	1.7	5.7	+4.0

Note: [a] the calculation of electricity consumption is after building envelope retrofits.

Table 7: Technical potential of natural gas savings in Xiamen households

Measures	**Thermal efficiency (%)**		**2011 Baseline (MJ/m^2·year)**	**Gas savings (MJ/m^2·year)**
	current average	advanced		
Tier-1 gas water heaters	88%	96%	3.5	0.26
Tier-1 built-in type gas cook stoves	51.5%	63.0%	51.8	9.46
Tier-1 desktop type gas cook stoves	56.5%	66%	35.6	5.12
		Total	**90.9**	**14.84**

Table 8: LCOCE of selected energy-saving measures for Xiamen’s residential buildings

Technical measures (TM)	**Details of technical measures**	**Calculated LCOCE by discount rates (DR)** (Yuan/kWh for electricity measures and Yuan/m^3 for natural gas measures)		
		DR=6%	**DR=8%** (reference case)	**DR=10%**
TM-1	Retrofitting building 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[a]	0.7516	0.8474	0.9484
TM-9	Adopting Tier-1 front-loading type washing machines	4.5569	4.9241	5.3041
TM-10	Adopting Tier-1 top-loading type washing machines	55.4524	59.9216	64.5459
TM-11	Adopting Tier-1 gas water heaters	14.2674	15.4173	16.6071
TM-12	Adopting Tier-1 built-in type gas cook stoves	2.6623	2.8769	3.0989
TM-13	Adopting Tier-1 desktop type gas cook stoves	0.7568	0.8178	0.8809

Note: [a] efficient-advanced refrigerators mean the ones consuming electricity about 0.38 kWh/day.

Table 9: Economic potential of energy savings in Xiamen's residential buildings

Technical 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 electric water heaters	0.73	21.5
Retrofitting building roofs	2.51[a]	28.5
Efficiency-advanced refrigerators[b]	12.13	17.8
Tier-1 gas cook stoves	14.58 (13.13[c])	87.4
Total	35.43 (33.98[c])	n/a

Note: [a] energy consumption reduction from room air conditioners; [b] efficient-advanced refrigerators mean the ones consuming electricity about 0.38 kWh/day; [c] the values in the brackets are calculated by considering the "replacement effect" of desktop type gas cook stoves by built-in type ones.

Table 10: Amendment of technical energy-saving potential in Xiamen households for the base year of 2016

Appliances	Energy savings from the base year of 2011 (MJ/m^2·year)	Reduced Percentage when using 2016 as the base year	Estimated energy savings from the base year of 2016 (MJ/m^2·year)
Tier-1 room air conditioners	3.00	14.8%	2.56
Efficiency-advanced refrigerators[a]	12.13	31.4%	8.32
Tier-1 rice cookers	0.51	10.0%	0.46
Tier-1 TVs	4.97	26.5%	3.65
Tier-1 washing machines	1.10	20.8%	0.87
Tier-1 electric water heaters	0.73	37.5%	0.46
Tier-1 gas water heaters	0.26	31.3%	0.18
Tier-1 built-in type gas cook stoves	9.46	19.0%	7.66
Tier-1 desktop type gas cook stoves	5.12	9.9%	4.61

Note: [a] efficient-advanced refrigerators mean the ones consuming electricity about 0.38 kWh/day.

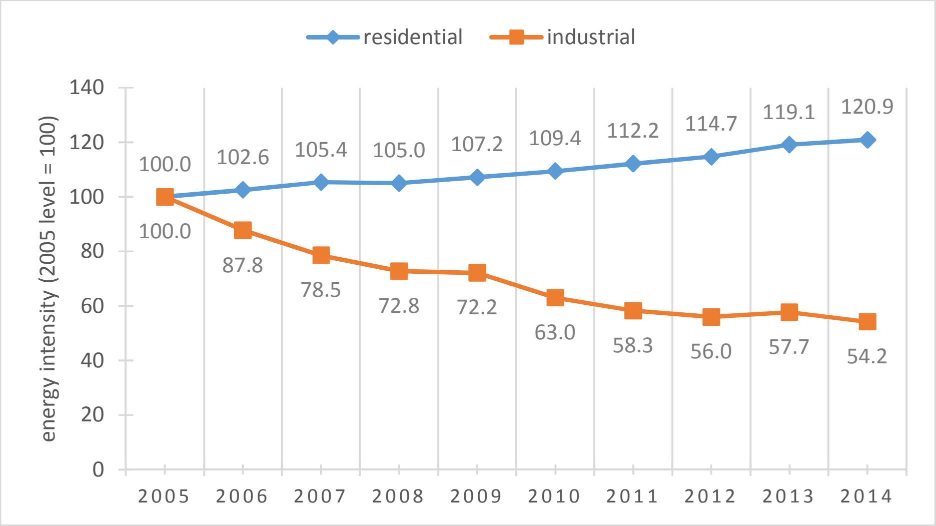
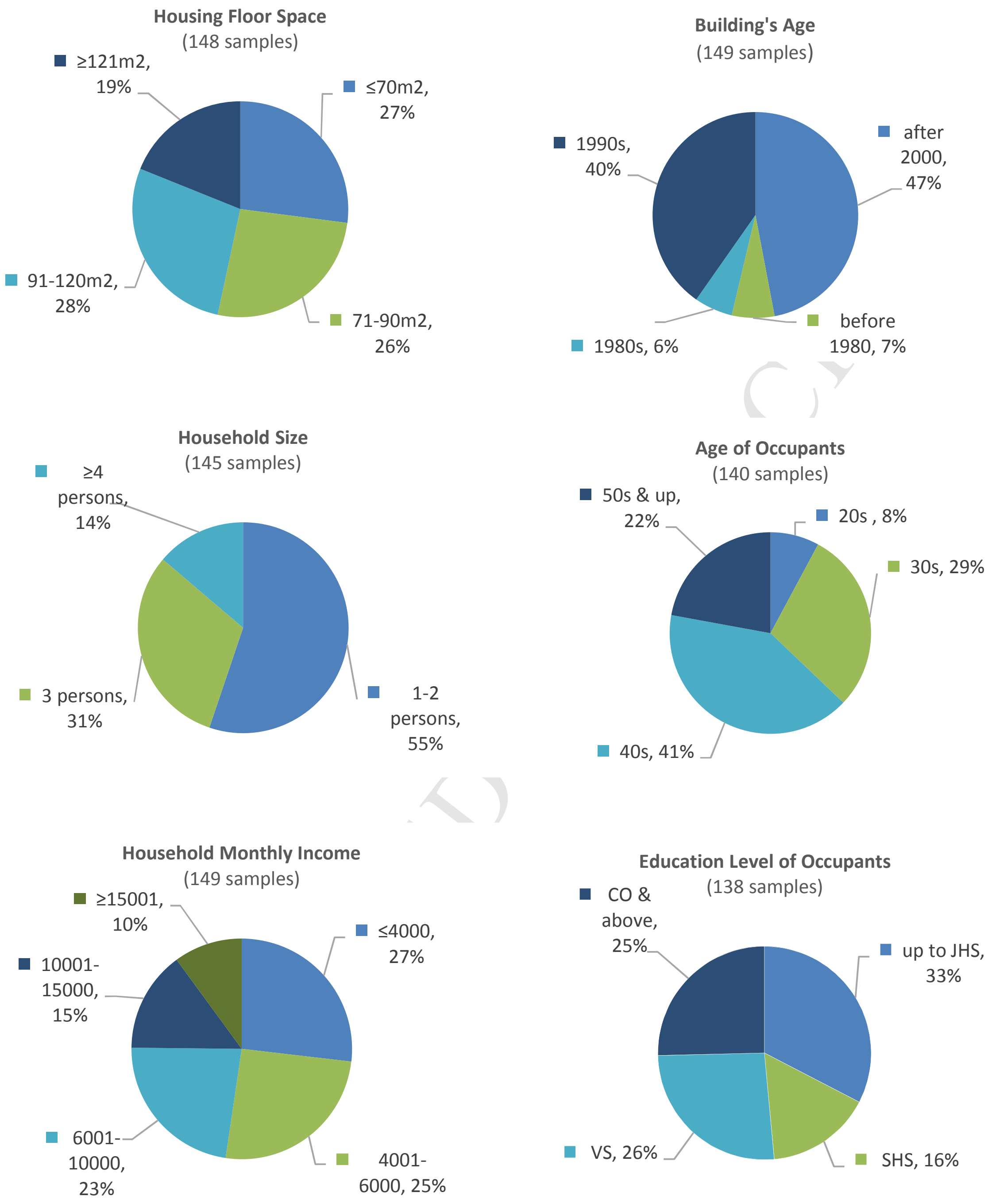


Figure 1: Trends of energy intensities of industrial and residential sectors in China [1,3,4,5]



Note: a) the income is in Chinese Yuan; b) as for education level, JHS (junior high schools), SHS (senior high schools), VS (vocational schools), and CO (colleges); c) the age and education level of occupants are those of the main income-earners of the households.

Figure 2: Distribution of our survey samples in key household features

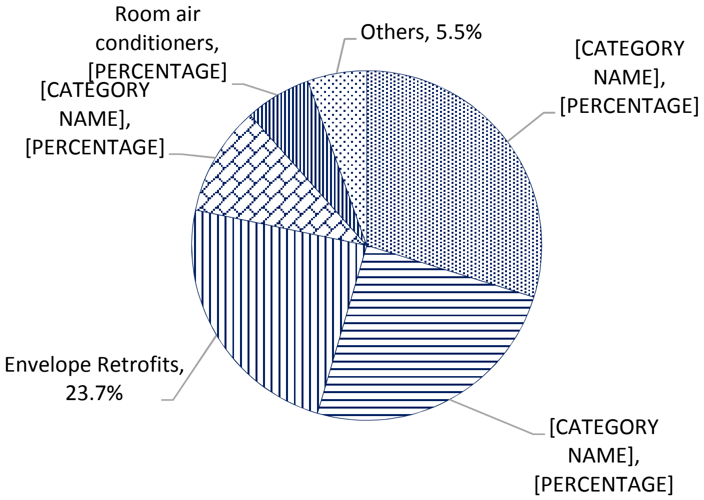


Figure 3: Distribution of the technical potential of residential energy savings in Xiamen

Highlights

A household energy use survey was conducted in Xiamen city of China.

The survey adopts a similar questionnaire used by the U.S. EIA’s RECS.

Large technical and economic energy saving potentials exist in Chinese households.

Levelised cost of conserved energy (LCOCE) was used for economic potential analysis.