An impact assessment of sustainable technologies for the Chinese urban residential sector at provincial level

Rui Xing, Tatsuya Hanaoka, Yuko Kanamori, Hancheng Dai and Toshihiko Masui
National Institute for Environmental Studies, Japan
E-mail: xing.rui@nies.go.jp

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Abstract
Recently, energy use in the urban residential sector of China has drastically increased due to higher incomes and urbanization. The fossil fuels dominant energy supply has since worsened the air quality, especially in urban areas. In this study we estimate the future energy service demands in Chinese urban residential areas, and then use an AIM/Enduse model to evaluate the emission reduction potential of CO₂, SO₂, NOₓ and PM. Considering the climate diversity and its impact on household energy service demands, our analysis is down-scaled to the provincial-level. The results show that in most of the regions, penetration of efficient technologies will bring CO₂ emission reductions of over 20% compared to the baseline by the year 2030. Deployment of energy efficient technologies also co-benefits GHG emission reduction. However, efficient technology selection appears to differ across provinces due to climatic variation and economic disparity. For instance, geothermal heating technology is effective for the cold Northern areas while biomass technology contributes to emission reduction the most in the warm Southern areas.

1. Introduction
Since 1990, China’s economy has grown fourfold and energy use has also drastically increased due to higher incomes and urbanization. The rising dominance of coal in the country’s energy mix has meant that energy-related greenhouse gas (GHG) emissions have grown faster than energy consumption (IEA 2010).

In the residential building sector, improvements in living standards have caused substantial growth of household-related CO₂ emissions. From 2000 to 2005, the total floor space of residential buildings has increased from 2.23 billion m² to 8.45 billion m², while floor area per capita increased 1.3-fold from 20.3 to 26.1 m² (NBSC 2010). In addition, the ownership of higher quality domestic appliances has also increased rapidly in urban areas of China due to income growth. Most urban households now have a refrigerator, washing machine, and color television. Every year the National Bureau of Statistics of China publishes a statistical yearbook that covers urban household year-end possession of durable consumers goods per 100 households. Since the late 1990s, the yearbook has excluded goods such as electric fans, black-and-white television sets and sewing machines, and has newly added computers, microwaves and air-conditioners. The surge in ownership of above mentioned electronics and other durable goods has increased energy consumption sharply.

The climate of China is extremely diverse, ranging from tropical regions in the South to subarctic areas in the North. Tremendous differences in latitude, longitude and altitude give rise to sharp variations in precipitation and temperature. The country is divided into five climatic areas for designing the built environment: severe cold; cold; hot summer/cold winter; temperate; and hot summer/warm winter. Central heating systems are provided in severe cold and cold areas during the winter season, while in the other three areas heating service is mainly provided by individual air-conditioners. Figure 1 shows that heating degree day 18 gradually decreases from North to South in China.

Other than the climatic characteristics, economic development level also has a huge impact on household energy service demands. Several empirical studies have argued about the associations between household expenditures and energy consumption (Rosas-Flores et al 2011, Chitnis and Hunt 2012, Dai et al 2012, Büchs et al 2013). Unlike climate characteristics, the gap of economic development level is between Eastern
China and Western China (figure 1). According to The Economist, per capita GDP in some coastal provinces of China is already as high as that in some EU countries. However, in some Western provinces per capita GDP is still at the same level of some least developed countries in the world (The Economist 2014).

The impact of climatic and socioeconomic diversity on building energy demand across Chinese provinces has drawn attention of policy makers recently. Yu et al have proposed a regional approach of estimating building energy demand by dividing China into four climactic areas (Yu et al 2014). However, with Beijing—one of the most developed regions in China—and some of the less developed Western regions in the same climatic area, it is difficult to examine the relationship between per capita income level and residential energy use intensity. Therefore, in this research we take each provincial level division as a subject. Both economic and climatic circumstances are taken into account while estimating energy service demand.

Several recent studies have investigated the historical and current Chinese residential energy consumption. The Annual Report on China Building Energy Efficiency (BEE) from Tsinghua University since 2007 (THUBERC 2011) and Liu et al (2011)’s study give us historical visions of household related energy consumption. Ning and Tonooka (2008) proposed an investigation of the growth of home appliance use in Shanghai. Moreover, Brockett et al (2002) and Yoshino et al (2009) conducted field studies that provide metered data on residential energy consumption to establish a baseline energy consumption profile for the Chinese urban residences. Feng et al (2011) and Chang et al (2013) estimated the household energy consumption with different approaches. However, these studies only address the current status and do not provide any energy efficiency resolution. Li et al (2015), Kong et al (2012) and Zhang et al (2013) thoroughly reviewed the current BEE policies in Chinese buildings without giving a clear vision of future impacts from the reviewed policies. Jiang and Hu (2006) proposed future energy demand scenarios of the Chinese residential sector. But in their study the differences in climate and economic conditions across regions were not considered.

This paper provides energy demand projection through 2030 on the provincial level. We first develop a macro-model to forecast residential energy service demand by Chinese administrative divisions taking into consideration the climatic characteristics of 31 Chinese province-level divisions. Then we select efficient technologies and use AIM/Enduse to evaluate the GHG emission reduction potential. This study addresses urban residential buildings and offers suggestions concerning future trends in GHG emission, as well as a cost-effectiveness assessment of efficient technologies.

Section 2 describes the methodology of estimating future service demands and evaluating GHG emission reduction potential. Section 3 shows the results of future service demands on provincial level, and efficient technologies’ impact on emission of CO2, SO2, NOx and PM. Section 4 gives an in-depth discussion on residential GHG emission issue and its possible solution for each Chinese province.

2. Methodology

2.1. Socioeconomic framework

In this research we use the shared socioeconomic pathways (SSPs)—a set of qualitative and quantitative narratives that describe future socioeconomic conditions to project socioeconomic indicators such as population, GDP and urban population share. SSPs were recently developed by the scientific community to enable the exploration of factors that are important for the assessment of future GHG emissions and mitigation and adaptation activities. The set of SSPs provides common assumptions about alternative future socioeconomic developments at the global, regional and national level in terms of population growth, education level, urbanization process, and economic development (van Vuuren et al 2012). In this study we use database of total population, urban population share and per capita GDP from SSP 1–3 to...
Table 1. The SSP storylines (taken directly from SSP database (IIASA 2012)).

| SSP                  | Storyline                                                                 |
|----------------------|---------------------------------------------------------------------------|
| SSP1 (Sustainability) | A world that aims at pursuing a sustainable development path to achieving development goals while reducing resource intensity and fossil fuel dependency. |
| SSP2 (Middle of the road) | The ‘business-as-usual’ world sees the trends typical of recent decades continuing, with some progress toward achieving development goals. |
| SSP3 (Fragmentation)  | A world that is separated into regions characterized by extreme poverty, pockets of moderate wealth, and a large number of countries struggling to maintain living standards for a rapidly growing population. |

build various future socioeconomic frameworks (table 1).

The original SSP database (IIASA 2012) only provides quantification data at country level. In order to conduct an analysis on provincial level, first we disaggregate the original national value to provincial values. During disaggregation the relationship between distance from one certain provincial value to the national average and distance from national average to the maximum or minimum provincial value stays the same as that in the benchmark year 2010. The compound population growth rate of each province is estimated by using equation (1)

\[
X_{t,r} = \left( X_{r, \text{max}} - X_{r, \text{ave}} \right) \times \frac{X_{t, \text{ave}} - X_{t, \text{min}}}{X_{t, \text{ave}} - X_{t, \text{min}}} 
\]

where \( X_{t,r} \) is the compound population growth rate in year \( t \) and province \( r \), \( X_{r, \text{ave}} \) is the national average of population growth rate in year \( t \) from SSPs, \( X_{r, \text{max}} \) is the assumed maximum value of population growth rate in year \( t \), \( X_{r, \text{min}} \) is the assumed minimum value of population growth rate in year \( t \), \( t_0 \) is the benchmark year (2010).

Based on the growth rate, the annual provincial population is estimated by using equation (2). And to keep the total population consistent with SSP2’s projection, we use equation (3) to adjust the provincial population

\[
\text{POP}_{r,t} = \text{POP}_{r,t-1} \times X_{t,r} \quad \text{(2)}
\]

\[
\text{POPN}_{t,r} = \text{POP}_0 \times \frac{\text{POP}_{t,r}}{\sum_{r'} \text{POP}_{r',t}} \quad \text{(3)}
\]

where \( \text{POP}_{t,r} \) is the provincial population in year \( t \) and province \( r \)

\( \text{POPN}_{t,r} \) is the adjusted regional population in year \( t \) and province \( r \), \( \text{POP}_0 \) is the national population in year \( t \) based on SSPs.

The urban population share and per capita GDP are both disaggregated to provincial level using the same methodology. Figure 2 illustrates the original and downscaled socioeconomic indicators from SSP2. Regions with high population density continually have higher population growth rate which results in high population densities in three provinces/regions—Beijing, Shanghai and Guangdong in 2100. With regard to urban population share and per capita GDP, the current growth trajectories are continued through 2100.

2.2. Energy service demand

In our research, we first use a macro-model (Xing and Ikaga 2013) to estimate future energy service demand. This model is a combination of engineering information and social-economic scenario settings. Figure 3 illustrates the general modeling process and main exogenous inputs.

For per capita floor area and household size we use extrapolation to estimate the future values (Xing and Ikaga 2013), while total urban population and per capita GDP are taken from SSPs (IIASA 2012). Projections for all 31 administrative divisions are listed in table A1 (household number), table A2 (household size) and table A3 (floor area). In yearbooks statistical data do not distinguish per capita GDP by urban and rural areas. Considering there is a huge gap of living standards between urban and rural areas in China, here we take per capita income value to estimate saturation factors. Future per capita income is calculated from per capita GDP (figure A1).

We also consider the effects of eight kinds of household electronics: washing machines, refrigerators, televisions, computers, stereo systems, microwaves, vacuum cleaners and cooking stoves. We extrapolate the numbers of electronics per household in 2030, with the exception of cooking stoves, which are always set to one unit per household with no future variation.

2.3. Model calibration

The energy usage settings in the service demand macro-model (Xing and Ikaga 2013) represent the standard lifestyle in developed countries. However, in a developing country such as China, due to limited financial resource these settings may not be fully applied. Service demand should increase with income and decrease with service price (Eom et al 2012). In economic terms, there is a saturation with energy service comfort, below which the marginal utility of an energy service is positive and above which the marginal utility...
Figure 2. Socioeconomic indicators of 31 Chinese provinces disaggregated from SSP2.

Figure 3. Flow chart of service demand estimation process.
turns negative (Anderson and Kushman 1987, Henley and Peirson 1997).

The preliminary estimations from the model appear to be much higher than statistical data (NBSC 2011) in base year (2010). Therefore as illustrated in figure 3 we introduce corrective coefficients —satiation factors to revise the model’s over-estimation. The revised service demand is calculated by using equation (4). Technological energy efficiencies in base year are average values of widely used devices (NIES 2012)

\[
ED_{r,s,t} = ESD_{r,s,t} \times EFF_{r,s,t,0},
\]

\[
= ESD_{r,s,t}^{\text{est}} \times SF_{r,s,t} \times EFF_{r,s,t,0},
\]

\[
= f(\text{area, household, energy behaviour, HDD, etc}) \times SF_{r,s,t} \times EFF_{r,s,t,0},
\]

where \( r \) is region or province, \( s \) is energy service, e.g. heating, hot water, cooking etc, \( e \) is energy carrier, e.g. oil, gas, electricity, coal, biomass etc, \( t \) is year, \( ED_{r,s,t} \) is annual energy demand, \( ESD_{r,s,t} \) is annual energy service demand from statistics, \( ESD_{r,s,t}^{\text{est}} \) is estimated annual energy service demand as a function of floor area, household number and size, income level, heating degree days, cooling degree days etc, \( SF_{r,s,t} \) is satiation factor, \( EFF_{r,s,t,0} \) is technological energy efficiency in 2010.

Satiation factors are coefficients which evaluate income induced service demands in the future and can be seen as a logistic function with per capita disposable household income as the explanatory variable (equation (5)). When the per capita disposable income reaches OECD average value 25596 US$ (year 2011, current prices and PPPs (OECD 2014)) in the future, satiation factor is manually set as 100%.

\[
SF_{r,s,t} = \frac{PCIC_{r,t}}{PCIC_{r,t} + a_t} \times \frac{25596}{25596}
\]

\[
SF_{r,s,t} = 100\% \text{ if } PCIC_{r,t} \geq 25596,
\]

where \( PCIC_{r,t} \) is annual per capita disposable household income (2011 US$) in urban area of province \( r \), \( a_t \) is logistic model parameter of energy services. The logistic model parameter \( a_t \) is determined by using the least square method as shown in equation (6). Bringing in satiation factors helps to keep model estimation consistent with historical data in the base year.

Minimizing: \( \varepsilon = \sum_{r,s,t} (ESD_{r,s,t,0} - ESD_{r,s,t,0}^{\text{est}})^2 \),
Subject to: \( ESD_{r,s,t,0}^{\text{est}} = ESD_{r,s,t,0} \times SF_{r,s,t,0} \). (6)

Figure 4 shows satiation factors of hot water use and other energy services in urban China. Here we use the Chinese average per capita income as an example. According to SSP2’s projection (figure 2), the average per capita income in urban China will surpass 25596 US$ in 2065, at which time the satiation factor will consequently reach 100%.

Figure 5 shows the comparison of statistical data (NBSC 2010) and model estimates of urban residential energy demands in 31 Chinese provinces in year 2010. The preliminary results from the model are much higher than statistical data, however after syncing satiation factors with the preliminary results, the calibrated model estimates have a close match with statistical data.

2.4. AIM/Enduse

In order to select effective efficient technologies for urban residential sector, we use the AIM/Enduse model (Kainuma et al 2003, Hanaoka et al 2015), a...
bottom-up optimization model with a detailed mitigation technology database, to estimate mitigation potential of sustainable policies. In the base year (2010) the estimated service demands are disaggregated to energy usage of existing technologies, while in the target year (2030) service demands are satisfied with energy efficient technologies. Efficient technologies are listed in table 2. For each household device, we

Table 2. List of technologies considered in AIM/Enduse.

| Device                        | Energy source                             | Efficiency          | Technology number |
|-------------------------------|-------------------------------------------|---------------------|-------------------|
| Heating                       |                                           |                     |                   |
| Coal stove                    | Coal                                      | Existing (EXT)      | 1                 |
| Central heating boiler        | Heat                                      | EXT, best available (BAT) | 2                 |
| Heating air conditioner       | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |
| Heating stove                 | Nature gas, biomass                       | EXT, BAT            | 4                 |
| Geothermal heating            | Geothermal                                | NEW                 | 1                 |
| Cooling                       |                                           |                     |                   |
| Cooling air conditioner       | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |
| Hot water                     |                                           |                     |                   |
| Nature gas water heater       | Nature gas                                 | EXT, BAT            | 2                 |
| Town gas water heater         | Coke oven gas, gas works gas              | EXT                 | 2                 |
| LPG water heater              | Liquefied petroleum gas (LPG)             | EXT, BAT            | 2                 |
| Electric water heater         | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |
| Solar water heater            | Solar thermal                             | EXT                 | 1                 |
| Biomass water heater          | Biomass                                   | NEW                 | 1                 |
| Cooking                       |                                           |                     |                   |
| Cooking range                 | Coal, nature gas, LPG, grid electricity, diesel electricity | EXT, BAT | 10                |
| Cooking range                 | Coke oven gas, gas works gas              | EXT                 | 2                 |
| Biomass cooking range         | Biomass                                   | NEW                 | 1                 |
| Lighting                      |                                           |                     |                   |
| Incandescent lamp             | Grid electricity, diesel electricity      | EXT, NEW            | 4                 |
| Fluorescent lamp              | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |
| LED                           | Grid electricity, diesel electricity      | EXT                 | 2                 |
| Electronics                   |                                           |                     |                   |
| Refrigerator                  | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |
| Television                    | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |
| Other equipment               | Grid electricity, diesel electricity      | EXT, NEW, BAT      | 6                 |

Table 3. Efficiencies/COPs of three technology levels.

| Device                                      | Efficiency (COP for air conditioner) |
|---------------------------------------------|---------------------------------------|
| Central heating boiler                      | 0.50                                  |
| Heating air conditioner (grid electricity)  | 2.80, 3.20, 6.34                      |
set an existing (EXT) technology with a low efficiency and one or more technologies (NEW and best available technology (BAT)) with high efficiencies. NEW technology is considered to have a higher efficiency and BAT is considered as a most efficient technology. Table 3 gives an example of three technology levels. Along with the existing technologies, 77 technologies in total are prepared in the AIM/Enduse model to estimation the emission reduction potentials. The model selects technology combination for each province under the least total-system cost.

For the model simulation we provide two future scenarios: baseline and countermeasure. In the baseline scenario the technology share stays the same as that in 2010. No sustainable technology is implemented in the baseline scenario. On the other hand in the countermeasure scenario we prepare a total number of 77 technologies include both traditional and efficient technologies. All the technologies then compete over cost-effectiveness.

3. Results

3.1. Energy service demands

Figure 6 shows the energy service demand of China and four Chinese regions in three different socioeconomic pathways. Beijing and Heilongjiang are representative regions in the cold Northern area, while Shanghai and Guangdong are representative regions in the warmer Southern area. The service demand of China in SSP1 and SSP3 grow and decline by 5% against the service demand level in SSP2 respectively. However, when it is downscaled to provincial level, the differential is quite small. In Guangdong—the biggest region of four representative regions this fluctuation range is around 5%. In three regions besides Guangdong energy service demands grow (SSP1) or decline (SSP3) by 3% against the BaU (SSP2) level. Therefore for the GHG emission analysis we use SSP2 only as a socioeconomic framework.

Figure 7 indicates the energy service demands of eight representative Chinese provinces from five climate zones under SSP2’s socioeconomic framework. For each climate zone, region in the top row has the highest urban per capita income and region in the bottom row has the lowest urban per capita income. In 2030, energy service demands of urban residential sector increase in all the regions compared to 2010. Most of the increase is caused by higher living standards and population growth. After 2020 when the population reaches peak the growth rate of service demand also starts to slow down. For the cold Northern regions heating service has the largest share of the total energy service demand, while in warm Southern regions the share of cooling service gradually increases. In comparison with the low income regions, households in high income regions have more expenditure on electronics amenities and therefore result in a higher share of household electronics in the total energy service demand.

3.2. GHG emission

Figure 8 shows the results of CO₂ emission reduction potential and its contributors in the Chinese urban residential sector. Overall, even without emission taxes, efficient technologies will penetrate the market and bring financial profit due to energy saving. The penetration of efficient technologies results in approximately 30% CO₂ emissions reduction by 2030 compared with the baseline scenario. In the
countermeasure scenario, efficient technologies of heating and hot water services make contributions to the bulk of the CO₂ emission reductions, while reductions from cooling service can hardly be observed in the figures, which indicates that without financial support from an emission tax policy, sustainable cooling technologies will not be implemented due to expensive initial costs.

Figure 9 indicates four kinds of GHG (CO₂, SO₂, NOₓ, PM) emission from urban residential sector in four representative regions with different building codes. CO₂ emission are mainly caused by use of heating services in cold areas like Beijing and Heilongjiang, where heating service are provided by coal. In warm areas like Shanghai and Guangdong CO₂ emission are mainly caused by using electronic equipment, which requires a large amount of electricity. The massive use of central heating services also leads to a significant amount of SO₂, NOₓ, and PM emissions. A small amount of SO₂ emissions caused by hot water service, which is mainly provided by natural gas, is also observed in the results. Only a little amount of NOₓ and PM emissions is observed in warm areas like Shanghai and Guangdong.

4. Discussion and conclusions

In this study 77 technologies of residential energy service (table 2) are provided for AIM/Enduse to choose in order to keep the lowest cost while bringing GHG emission reduction. Although the 31 Chinese provinces targeted are equally given the technology options, model selected technologies appear to be different. Figure 10 illustrates the major efficient technologies that bring the biggest amount of CO₂ emission reductions in four representative provincial areas.

In this study, biomass (wood residuals) is considered as a carbon neutral energy source and therefore shows its importance to CO₂ emission reduction. Regarding CO₂ emission reduction, biomass cooking range (NEW) and fluorescent lamp (NEW) are chosen.
for all four regions. In cold regions like Heilongjiang and Beijing, where heating service shares a huge amount of total energy service demand, geothermal heating (NEW) is the biggest contributor to CO₂ emission reduction. On the other hand in warm regions biomass water heater is the biggest contributor. Some of these technologies also bring co-benefits by reducing other three gas emissions.

**Figure 9.** GHG emissions from urban residential sector.

**Figure 10.** CO₂ emission reduction contributors in four provincial areas.
Because of its low emission factors, biomass appears to have advantages of bringing co-benefits compare with other fossil fuels. In cold Northern areas, implementation of geothermal heating device and biomass cooking range contribute to emission reductions of all four GHGs. In the warm Southern areas, the co-benefiting technology is biomass water heater (NEW). In our results, fluorescent lamp (NEW) and TV (BAT) are important to CO₂ emission reduction but bring no co-benefits for SO₂, NOₓ and PM emission reductions.

This research includes only the preliminary results of our model simulation. First, emission tax is not included in the countermeasure scenario. We examine only the energy savings brought by efficient technologies. In our future studies financial instruments will be considered during scenario designing. Second, in this research energy efficient technologies are allowed to be fully penetrated in the market. Sometimes this will result in an unnatural growth of technology share during a short time period which is not feasible for the real world. In the next step constraints of specific technologies will also be considered through the target period of time. Last but not least, in China there are six electric power companies who provide electricity to 31 provinces. However in this study we only focus on residential sector under the assumption of all 31 provinces using a nation grid. Therefore in this study we use average emission factor of electricity for all 31 Chinese provinces. In the future we are planning to link electricity supply sector with demand sector in AIM/Enduse model. Varieties of electricity generation sources (e.g. share of hydropower) across provinces will be integrated into the model.

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Appendix

| Table A1. Regional household numbers (millions). |
|----------------------------------------------|
| 2010 | 2015 | 2020 | 2025 | 2030 |
| Heilongjiang | 7.60 | 7.80 | 7.94 | 8.31 | 8.67 |
| Inner-Mongolia | 4.69 | 4.95 | 5.18 | 5.54 | 5.88 |
| Qinghai | 0.71 | 0.83 | 0.96 | 1.04 | 1.12 |
| Tibet | 0.14 | 0.22 | 0.29 | 0.34 | 0.39 |
| Xinjiang | 2.57 | 3.21 | 3.85 | 4.40 | 4.96 |
| Jilin | 4.83 | 4.97 | 5.08 | 5.45 | 5.80 |

| Table A1 (Continued.) |
|------------------------|
| Liaoning | 9.67 | 10.18 | 10.62 | 11.16 | 11.68 |
| Beijing | 5.13 | 6.88 | 8.68 | 10.28 | 11.92 |
| Tianjin | 2.65 | 3.28 | 3.92 | 4.37 | 4.82 |
| Hebei | 9.63 | 11.19 | 12.73 | 13.82 | 14.90 |
| Shandong | 16.56 | 18.66 | 20.70 | 22.36 | 24.01 |
| Ningxia | 0.85 | 1.00 | 1.15 | 1.28 | 1.41 |
| Sichuan | 11.66 | 12.92 | 14.11 | 14.67 | 15.20 |
| Shaanxi | 5.68 | 6.48 | 7.26 | 7.82 | 8.36 |
| Shanxi | 5.17 | 6.08 | 6.98 | 7.66 | 8.34 |
| Gansu | 2.62 | 3.03 | 3.44 | 3.67 | 3.90 |
| Shanghai | 5.81 | 8.08 | 10.56 | 12.87 | 15.39 |
| Anhui | 8.08 | 9.03 | 10.06 | 10.91 | 11.83 |
| Henan | 11.39 | 12.92 | 14.42 | 15.21 | 15.98 |
| Jiangsu | 11.09 | 12.46 | 14.11 | 15.25 | 16.66 |
| Hubei | 8.76 | 9.47 | 10.21 | 10.49 | 10.78 |
| Jiangxi | 5.48 | 6.01 | 6.59 | 6.97 | 7.36 |
| Yunnan | 4.66 | 5.85 | 7.04 | 7.82 | 8.60 |
| Guizhou | 3.62 | 3.88 | 4.17 | 4.28 | 4.40 |
| Guangxi | 5.45 | 5.89 | 6.35 | 6.62 | 6.91 |
| Guangdong | 18.98 | 23.68 | 28.39 | 33.51 | 38.70 |
| Fujian | 6.92 | 7.51 | 8.08 | 8.82 | 9.55 |
| Hainan | 1.12 | 1.30 | 1.48 | 1.64 | 1.80 |

| Table A2. Regional household size (persons). |
|--------------------------------------------|
| 2010 | 2015 | 2020 | 2025 | 2030 |
| Heilongjiang | 2.84 | 2.77 | 2.71 | 2.67 | 2.64 |
| Inner-Mongolia | 2.90 | 2.83 | 2.79 | 2.75 | 2.73 |
| Qinghai | 3.57 | 3.49 | 3.44 | 3.39 | 3.36 |
| Tibet | 4.57 | 4.43 | 4.34 | 4.27 | 4.22 |
| Xinjiang | 3.48 | 3.42 | 3.39 | 3.36 | 3.35 |
| Jilin | 3.01 | 2.94 | 2.90 | 2.87 | 2.84 |
| Liaoning | 2.83 | 2.76 | 2.71 | 2.67 | 2.64 |
| Beijing | 2.66 | 2.58 | 2.52 | 2.47 | 2.43 |
| Tianjin | 3.26 | 3.21 | 3.18 | 3.15 | 3.13 |
| Hebei | 3.26 | 3.21 | 3.18 | 3.15 | 3.13 |
| Shandong | 2.86 | 2.81 | 2.78 | 2.76 | 2.74 |
| Ningxia | 3.53 | 3.48 | 3.45 | 3.42 | 3.40 |
| Sichuan | 2.93 | 2.84 | 2.78 | 2.73 | 2.69 |
| Shaanxi | 3.11 | 3.00 | 2.92 | 2.86 | 2.81 |
| Shanxi | 3.24 | 3.14 | 3.07 | 3.02 | 2.98 |
| Gansu | 3.70 | 3.62 | 3.57 | 3.52 | 3.48 |
| Shanghai | 2.79 | 2.65 | 2.52 | 2.40 | 2.28 |
| Anhui | 3.39 | 3.22 | 3.06 | 2.92 | 2.77 |
| Henan | 3.34 | 3.30 | 3.27 | 3.25 | 3.23 |
| Jiangsu | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Chongqing | 2.73 | 2.60 | 2.51 | 2.45 | 2.39 |
| Hunan | 3.26 | 3.32 | 3.36 | 3.38 | 3.40 |
| Zhejiang | 2.80 | 2.78 | 2.77 | 2.76 | 2.75 |
| Hubei | 3.03 | 2.97 | 2.92 | 2.89 | 2.86 |
| Jiangxi | 3.62 | 3.74 | 3.82 | 3.87 | 3.92 |
| Yunnan | 3.54 | 3.46 | 3.41 | 3.37 | 3.34 |
| Guizhou | 3.63 | 3.69 | 3.72 | 3.75 | 3.77 |
| Guangxi | 3.62 | 3.69 | 3.73 | 3.76 | 3.79 |
| Guangdong | 3.26 | 3.12 | 3.03 | 2.96 | 2.90 |
| Fujian | 2.99 | 2.93 | 2.89 | 2.86 | 2.83 |
| Hainan | 3.77 | 3.70 | 3.65 | 3.61 | 3.58 |
Table A3. Regional residential floor area (million m²).

| Region       | 2000   | 2005   | 2010   | 2015   | 2020   | 2025   | 2030   |
|--------------|--------|--------|--------|--------|--------|--------|--------|
| Heilongjiang | 122.00 | 311.53 | 336.79 | 385.86 | 430.53 | 468.71 | 499.47 |
| Inner-Mongolia | 45.55  | 152.59 | 177.70 | 201.92 | 224.09 | 243.00 | 258.31 |
| Qinghai      | 6.94   | 23.10  | 34.38  | 38.83  | 42.92  | 46.40  | 49.29  |
| Tibet        | 2.97   | 8.02   | 50.31  | 57.81  | 64.42  | 70.05  | 74.69  |
| Xinjiang     | 37.05  | 107.08 | 210.28 | 242.23 | 271.04 | 295.58 | 316.09 |
| Jilin        | 74.12  | 177.88 | 194.96 | 219.07 | 241.31 | 260.20 | 275.12 |
| Liaoning     | 171.66 | 314.84 | 382.02 | 436.60 | 486.36 | 528.86 | 562.77 |
| Beijing      | 77.83  | 202.45 | 204.88 | 220.32 | 235.34 | 247.83 | 257.13 |
| Tianjin      | 45.03  | 98.30  | 113.33 | 121.83 | 130.39 | 137.62 | 143.11 |
| Hubei        | 101.78 | 365.62 | 456.24 | 497.18 | 536.77 | 570.24 | 597.00 |
| Shandong     | 176.41 | 489.59 | 513.40 | 578.98 | 636.58 | 684.61 | 722.64 |
| Ningxia      | 10.10  | 34.90  | 45.32  | 46.47  | 48.07  | 49.38  | 50.30  |
| Sichuan      | 97.06  | 389.99 | 436.11 | 454.46 | 474.82 | 491.40 | 502.70 |
| Shaanxi      | 47.17  | 152.63 | 189.27 | 198.81 | 208.71 | 216.72 | 222.37 |
| Shanxi       | 62.97  | 200.64 | 399.71 | 487.31 | 561.52 | 624.28 | 676.23 |
| Gansu        | 33.79  | 106.20 | 140.12 | 148.13 | 156.26 | 162.90 | 167.87 |
| Shanghai     | 120.25 | 265.98 | 299.39 | 350.27 | 396.11 | 435.46 | 467.75 |
| Anhui        | 61.52  | 216.86 | 235.71 | 238.27 | 243.83 | 248.26 | 250.84 |
| Henan        | 106.27 | 396.40 | 432.08 | 432.64 | 437.33 | 439.80 | 438.87 |
| Jiangsu      | 152.12 | 530.85 | 674.35 | 769.12 | 853.81 | 925.40 | 983.04 |
| Chongqing    | 46.50  | 161.78 | 209.98 | 240.47 | 268.23 | 291.96 | 311.31 |
| Hunan        | 96.28  | 317.12 | 421.54 | 477.49 | 527.92 | 570.55 | 605.45 |
| Zhejiang     | 119.94 | 522.63 | 608.00 | 592.47 | 665.17 | 726.29 | 775.90 |
| Hubei        | 131.74 | 306.46 | 356.28 | 400.69 | 441.61 | 476.41 | 504.35 |
| Jiangxi      | 46.84  | 196.03 | 233.25 | 224.82 | 222.12 | 220.52 | 218.62 |
| Yunnan       | 38.19  | 158.35 | 195.86 | 199.07 | 204.55 | 208.98 | 211.73 |
| Guizhou      | 27.65  | 89.72  | 115.95 | 127.28 | 137.96 | 146.96 | 154.21 |
| Guangxi      | 47.58  | 199.22 | 239.73 | 244.31 | 251.54 | 257.41 | 261.31 |
| Guangdong    | 155.28 | 702.77 | 853.93 | 884.75 | 920.45 | 949.27 | 969.05 |
| Fujian       | 57.84  | 226.15 | 286.19 | 327.54 | 365.21 | 397.40 | 423.97 |
| Hainan       | 20.43  | 38.01  | 50.85  | 52.66  | 54.85  | 56.67  | 58.00  |

\[ y = 0.4813x + 652.39 \]
\[ R^2 = 0.9873 \]

Figure A1. Calculating per capita income from per capita GDP (2011US$).
Figure A2. Energy service demand of 31 Chinese provinces in SSP2.

Figure A3. Projected ownership rates of home appliances in Beijing’s urban households (same database for other 30 provinces).
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Figure A4. Socioeconomic indicators of 31 Chinese provinces.

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