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Energy Service Demand Projections and CO_2 Reduction Potentials in Rural Households in 31 Chinese Provinces

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Abstract: Until 2012, most of China's population lived in rural areas with markedly different patterns of household energy consumption from those in Chinese cities. The studies so far done on residential energy use in rural Chinese households have been limited to questionnaire surveys and panel data analyses. Hardly any studies on energy demand in rural areas have considered both the climatic and economic disparities across Chinese regions. In this study we conduct a systematic analysis of the rural Chinese residential sector on a regional basis. We begin by developing a macro-model to estimate energy service demands up to 2050. Next, we apply the AIM(Asia-Pasific Integrated Model)/Enduse model, a bottom-up cost-minimization model with a detailed mitigation technology database, to estimate the mitigation potential of low-carbon technologies in rural China. Our results show that energy service demand in the rural household sector will continue to increase in regions with growing population or income conditions. However, after 2030, the rural residential energy service demand will start to decline in most Chinese regions. The impacts of efficient technologies will vary from one region to the next due to regional climatic and economic disparities. Throughout all of China, the penetration of efficient technologies can reduce CO_2 emissions by 20% to 50%. Of the technologies available, efficient lighting, biomass water heaters, and efficient electronics bring the most benefit when implemented in rural households.

Keywords: China; rural household; Shared Socioeconomic Pathways; CO_2 emission; efficient technology

1. Introduction

Most of China's people lived in rural areas until 2011, when the urban population surpassed the rural population for the first time due to the country's rapid urbanization. As of now there are still over 650 million people and 210 million households [1] in the countryside. The types of housing and household energy structures markedly differ between urban and rural areas in China. The differences are so substantial that most of the studies done so far on Chinese energy demand have treated urban and rural households as two different sectors [2–4].

In the last century only a few studies looked into the energy service demand of China's rural households. Technology share and energy consumption were rather unclear when compared to the urban households. With China's rapid economic growth, living standards have sharply risen and the gap between the urban and rural economies has steadily narrowed (Figure 1, right). Rural residential service demand is drawing more attention from energy researchers. Several of the first attempts to open the "black box" in the research have relied on questionnaire survey methodologies [4–6]. While questionnaire surveys cover rural households incompletely, they do provide a representative energy consumption profile of Chinese rural residences in certain areas.

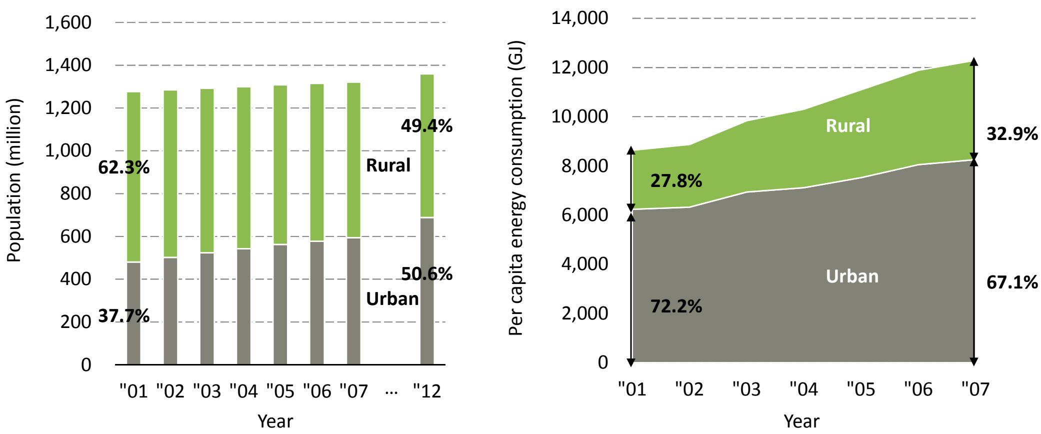

Figure 1. China's population (**left**, [7]) and per capita residential energy consumption (**right**, [8]).

The estimation of energy service demand on a national scale requires more systematic methods. Krey *et al.* [9] used three integrated assessment models to evaluated rural energy use in Asian countries and carried out a comparison study based on their results. Fan *et al.* [2] and Feng *et al.* [10] analyzed panel data to examine CO_2 emissions and energy use in China's rural households, respectively. All three of these studies were conducted at the country level in spite of the huge disparities in income and climate across regions and provinces. Household energy service demand is often associated with income and expenditure [11–14]. Zhao *et al.* [4] surveyed household energy consumption in four kinds of Chinese regions and examined the impact of the population scale and per capita income on per household energy consumption. Their method, however, resulted in the same per household energy consumption in cold and warm areas with the same per capita income (e.g., Beijing and Shanghai). This result clearly diverges from the reality, because cold areas have much higher energy consumption due to space heating services in the winter season. Yu *et al.* [15] proposed a regional approach of estimating building energy demand by dividing China into four climatic areas. However, their study put Beijing, a highly developed region with a much higher disposable income to expend on energy services, in the same climatic area as some of the less developed regions of the west.

China has the third largest territory in the world and an extremely diverse climate. The country is divided into five climatic areas ([16], Supplementary Figure S1) for designing the built environment: severe cold; cold; hot summer/cold winter; temperate; and hot summer/warm winter. Buildings in cold and severe cold areas are heated by central heating systems, while those in the other three areas are heated mainly by standalone air conditioners. As shown in Figure 2, the heating degree day 18 gradually decreases from north to south in China [17]. Economic inequality, meanwhile, has posed a major challenge to Chinese society in recent years. According to *The Economist* [18], the per capita GDP in some coastal provinces of China is already as high as that in some European countries. However, in some western provinces, the per capita GDP is still at the same level as some of the world's least developed countries (Figure 2, [18]).

Given this complex background, researchers cannot expect to evaluate household service demands in China solely on the basis of socioeconomic indicators or climate characteristics. Hardly any of the studies conducted so far have fully considered the regional disparities in climate or economy. The present study disaggregates China to the provincial level and looks into the patterns of rural residential energy demand in each provincial region. We first develop a macro-model to estimate future outlooks on rural residential energy service demand up to 2050. Then we use the AIM/Enduse model to evaluate the CO_2 emission reduction potential in order to analyze the effects of energy-efficient technologies. The study focuses on rural residential buildings and offers suggestions concerning future trends in CO_2 emission.

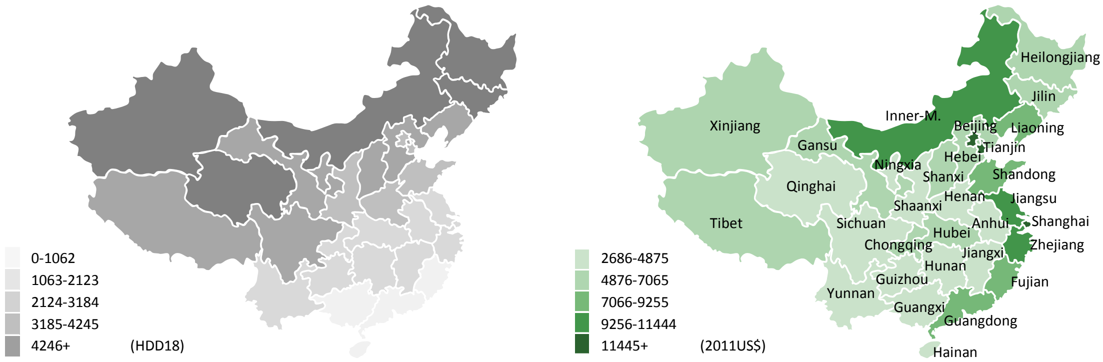

Figure 2. Heating degree day 18 (**left**) and per capita GDP (**right**) of 31 Chinese provinces.

The remainder of this paper is structured into Section 2, Section 3 and Section 4. Section 2 describes the methodology for estimating future service demand and evaluating the CO_2 emission reduction potential. Section 3 presents the results of our estimations of future service demand, energy consumption, and CO_2 emissions at the provincial level. Section 4 discusses the technology selection in detail and presents key conclusions.

2. Estimation of Service Demand

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 the urban population share. The SSPs are translated into five storylines based on worlds with various challenges for mitigation and adaption [19,20]. Each SSP storyline describes a different socioeconomic circumstance of the future. In this study we use SSP2[3], a storyline describing a "business-as-usual" world where the typical trends of recent decades continue, with some progress toward achieving development goals.

The original SSP database [21] only provides quantification data at the country level. To conduct our analysis at the provincial level, we disaggregate the original national value to provincial values ([22], Supplementary File S1). Consistent with SSP2's "business-as-usual" storyline, the difference between the provincial value and national value in a base year is assumed to stay the same up to 2050. The compound population growth rate and urban population share of each province are both disaggregated in this manner. Figure 3 (left) shows the results of a regional rural population projection. With the progress of urbanization in China, the rural population is expected to continue falling. As Krey *et al.* [9] point out, differences in behavior between urban and rural households may lead to different future emission pathways with high or low urbanization levels. Urbanization is considered a key driver of energy service demand in this study. Meanwhile, the household size is extrapolated up to 2050 based on the past trend (Figure 3, right). Households are larger in rural areas than in cities in China, as the "One-child Policy" is generally waived in the countryside. The projection, however, shows that households will keep shrinking even in rural areas.

The growth rate of per capita GDP is another principal driver of future energy demand, but one that fails to distinguish between urban and rural families. In this study we use per capita income as an economic indicator instead. Specifically, provincial per capita GDP is disaggregated from SSP2 (Figure 4, left) and a linear regression is performed to convert the GDP to rural income (Figure 4, right).

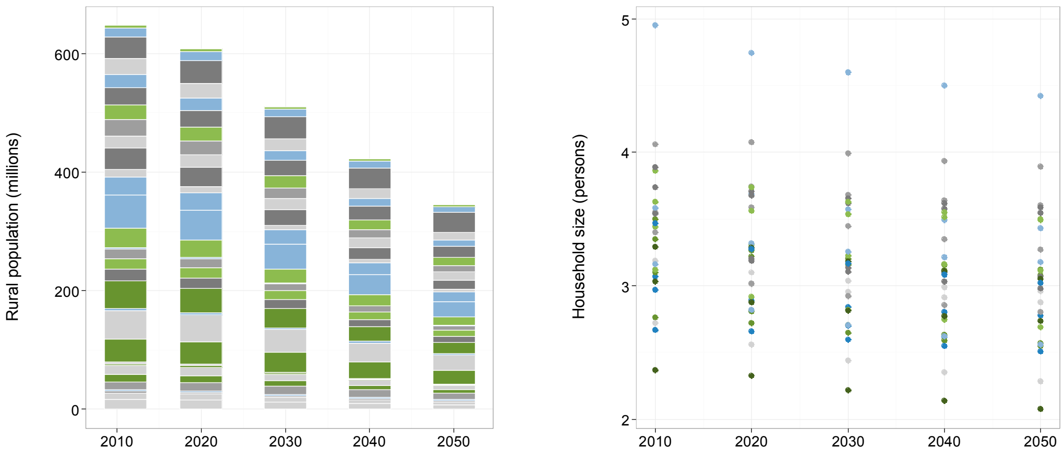

Figure 3. Rural population (**left**) and household size (**right**) of 31 Chinese provinces.

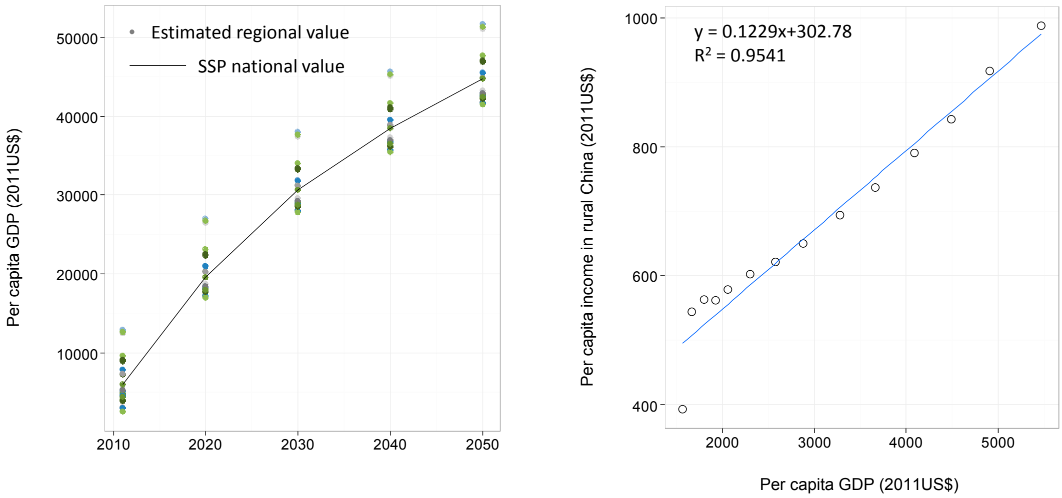

Figure 4. Regional per capita GDP (**left**) and historical (1997–2010) rural income (**right**, [7]).

Besides total population and per capita GDP, the dwelling floor area and ownerships of household electronics are also key indicators in estimating the future energy service demand. To begin determining the dwelling floor area, a regression analysis (Supplementary File S2, Table S5) is performed on panel data of the per household floor area between 2000 and 2012 [7]. Next, the regression equation is used to extrapolate the past trend of per household floor area up to 2050. These projections follow the story line of SSP2—"a development pathway that is consistent with typical patterns of historical experience" [19]. These data are then synced with data on the total number of households to determine the total floor area. Regional projections of floor area are listed in Supplementary Table S1. The household electronics component of our model consists of four types of electric appliances (white goods and brown goods): televisions, refrigerators, washing machines, and computers. The ownership projections for these goods are listed in Supplementary Table S2.

2.2. Energy Service Demand

In our previous research we designed a macro-model [22,23] to estimate the future energy service demand of the urban residential sector. Rural energy service demand in the present study is estimated in the same manner, while the input databases on indicators such as the number of households, floor area, *etc.*, are replaced with rural ones. In urban areas, space cooling service is also considered as a major residential energy service in China's warm regions [22]. However, cooling devices are rarely used in rural families. Although the usage of cooling services is highly influenced by income level, through the past 20 years there is no evidence suggesting that cooling services have widely penetrated in China's rural households [2,5,6,24]. Therefore, in this study, cooling service is excluded and energy service demand in the rural residential sector is categorized into five applications: heating, hot water, cooking, lighting, and electronics. Figure 5 describes the general modeling process and main exogenous inputs of the household applications.

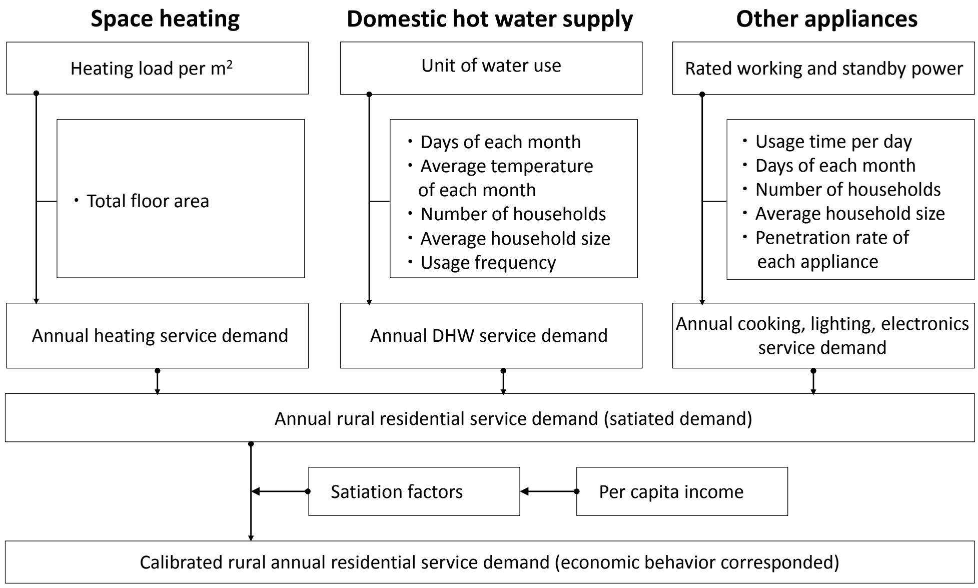

Figure 5. Flow chart of the service demand estimation process.

The annual space heating service demand is calculated using Equation (1). The annual heating service demand per unit (m^2) is taken from Zhang *et al.* [17].

$$HL_{r,t} = HLU_r \times DS_{r,t} \quad (1)$$

where

r:	The region
t:	The year
$HL_{r,t}$:	The annual heating service demand
HLU_r:	The annual heating service demand (ktoe/m^2) per unit (m^2)
$DS_{r,t}$:	The rural residential floor area

The domestic hot water (DHW) service demand for face-washing, cooking, and showering is calculated using Equation (2). The usage of hot water per activity and hot water supply temperature are taken from standard household models [25]. The tap water temperature is calculated from the average seasonal temperature.

$$DL_{r,t} = POP_{r,t} \times \sum_{s}\sum_{i} c\rho V_i \left(TS_i - TT_{r,s}\right) \times F_{r,s,i} \quad (2)$$

where

i:	DHW activity (face-washing, showering, and cooking)
s:	The season (summer, winter, and others)
c:	The heat capacity of water ((kJ/kg·°C)
ρ:	The density of water
$DL_{r,t}$:	The annual DHW service demand (ktoe)
V_i:	The usage of hot water per activity (L)
$POP_{r,t}$:	The population

TS_i: The hot water supply temperature (universal)
$TT_{r,s}$: The average tap water temperature (regional, seasonal)
$F_{r,s,i}$: The activity frequency per season

The modeling structure of the other three applications builds on the operating characteristics of each energy-consuming appliance. It can generally be expressed as Equation (3).

$$OTL_{r,t} = U_r \times A_{r,t} = f\,(working\ power,\ operation\ time, etc.) \times A_{r,t} \quad (3)$$

where

$OTL_{r,t}$: The service demand (ktoe) of lighting, cooking, and electronics
U_r: The annual service demand per unit (cooking range, *etc.*) or per m^2
$A_{r,t}$: The amount of service end users (total electronic units or total floor area)

Table 1 summarizes the operating characteristics of lighting, cooking, and the four white/brown goods composing household electronics. Most of the designed working powers and standard operation times are taken from the SCHEDULE program [25]. The service demand for cooking stoves is a function of the average household size. As explained in Section 2.2, we extrapolate the numbers of durable consumer goods per household in 2050, with the exception of cooking stoves, which are always set to one unit per household with no future variation. The usage patterns listed in Table 1 describe the general conditions in a standard family of a developed country. For Chinese rural families, the usage patterns need to be adjusted to cope with their lower income level (Section 2.3).

Table 1. Operation conditions of household appliances.

Appliance	Working Power (W)	Standby Power (W)	Operation Time (H/Day)
Washing machine	86.00	0.00	1.00
Refrigerator	20.80^2	0.00	24.00
TV set (color)	60.50	0.40	8.00
Computer	100.00	10.00	8.00
Cooking range	234.6 × HS + 253.2	0.00	6.00
Lighting device	5.00 (W/m^2)	0.00	6.00

HS: household size (persons per household).

2.3. Model Calibration

The frequency of hot water activity, electronics operation time, and other energy usage settings described above more or less represent the standard lifestyle in a developed country. In a less developed region such as rural China, limited financial resources may prevent these settings from being fully applied. Service demand should increase with income and decrease with service price [9,26]. In economic terms we can identify a satiation point for energy service comfort: below the satiation point the marginal utility of an energy service is positive; above it, the marginal utility turns negative [27,28]. In the current study we evaluate income-induced service demand in the future by introducing satiation factors to calibrate our model estimates. The satiation factor of each energy service can be described as a logistic function with per capita income as the explanatory variable ([22]; Equation (4)). When the per capita disposable income reaches the OECD (Organisation for Economic Co-operation and Development) average of 25,596 US$ (year 2011, current prices and purchasing power parity [29]) in the future, the satiation factor is manually set as 100%.

$$SF_{r,sv,t} = \frac{PCI_{r,t}}{PCI_{r,t} + a_{sv}} \times \frac{25596 + a_{sv}}{25596}\ PCI_r < 25596 \quad (4)$$

$$SF_{r,sv,t} = 100\%\ PCI_r \geqslant 25596$$

where

sv:	Energy service, e.g., heating, hot water, cooking, *etc.*
a_{sv}:	A logistic model parameter of energy services *sv*
$SF_{r,sv,t}$:	The satiation factor
$PCI_{r,t}$:	Per capita income

In the macro-model from our previous study (Xing *et al.*, 2015 [22]) we determined the satiation factors for certain energy services using the least squares method, as shown in Equation (5). Rural households, however, rely on non-commercial biomass, most of which is collected directly from the fields. The accurate total amount of non-commercial biomass consumption is difficult to tally, and no energy consumption data for the base year (2010) are available in the statistical yearbooks. Without this information, we must assume that the per capita income induces service demand just as it does in urban households and use the same satiation functions to calibrate the model results (Equation (6)).

Minimizing:

$$\varepsilon = \sum_{r,sv} \left(ECU^{stat}_{r,sv,t0} - ECU^{estm}_{r,sv,t0} \right)^2 \tag{5}$$

Subject to:

$$ECU^{stat}_{r,sv,t0} = ECU^{estm}_{r,sv,t0} \times SF_{r,sv,t0}$$

where

sv:	Energy service, e.g., heating, hot water, cooking, *etc.*
t0:	The base year (2010)
$ECU^{stat}_{r,sv,t0}$:	The annual energy consumption (urban) from statistics (NBSC, 2011)
$ECU^{estm}_{r,sv,t0}$:	The estimated annual energy consumption (urban)

$$ESD'_{r,sv,t} = ESD^{estm}_{r,sv,t} \times SF_{r,sv,t} \tag{6}$$

where

$ESD'_{r,sv,t}$:	The calibrated annual energy service demand (rural)
$ESD^{estm}_{r,sv,t}$:	The estimated annual energy service demand (rural)

2.4. AIM/Enduse

We select effective and efficient technologies for the rural residential sector by estimating the mitigation potential of sustainable policies using the AIM/Enduse model [30,31], a bottom-up cost-minimization model with a detailed mitigation technology database. In the base year (2010) the estimated service demands are disaggregated to the energy usage of existing technologies, while in the target year (2050) service demands are satisfied with a combination of existing technologies and efficient technologies. For each household appliance we set an existing (EXT) technology with a low efficiency and one or more technologies with high efficiencies (NEW and BAT). NEW technology is considered more efficient and BAT (best available technology) is considered the most efficient. The technological energy efficiencies in the base year are average values for widely used electric appliances [32]. The technology shares in the base year are taken from empirical studies [33–37]. Table 2 gives an example of the technology levels. A total of 83 existing, new, and best available technologies are prepared for the estimation of emission reduction potentials in the AIM/Enduse model (Supplementary Table S3). The model selects a technology combination for each province based on a least total system cost. The emission factors that are used to estimate CO_2 emission are taken from AIM/Enduse-Global ([38], Supplementary Table S6).

Table 2. Efficiencies (provided/consumed) of three technology levels.

Device	Efficiency		
	EXT	NEW	BAT
Coal stove (heating)	0.39	-	0.80
Refrigerator	0.63	1.00	1.43

2.5. Scenario Setting

For the model simulation we prepare two scenarios to evaluate the CO_2 emission growth and reduction potential: the Fix (FIX) and Cost-effective selection (CES) scenarios. In FIX the technologies can be regarded as frozen: the technology level remains at the base year (2010) level and no efficient technologies are implemented in the future. FIX is designed to offer a baseline picture of how CO_2 emissions will increase without any efficient technology intervention. In CES, efficient technologies stored in technology databases are allowed to penetrate the future market. Traditional technologies and efficient technologies compete over cost-effectiveness. In other words, CES describes a natural implementation process for efficient technologies.

The model basically allows the choice of any efficient technology to achieve a minimum total system cost. Two constraints take effect, however, during this process. The first constraint addresses the future share of non-commercial energy. Non-commercial energy sources such as firewood or straw currently account for over 80% of the rural residential energy demand [39]. Most of the non-commercial energy is collected by household members and has no commercial price, which makes it easy for the model to choose. However, the burning of these non-commercial fuels in indoor environments can cause serious air pollution problems. For this reason, CES does not encourage the use of non-commercial energy or set the share of non-commercial energy beyond the current (2010) level. The second constraint addresses the future share of renewable energy. The applications of renewable energy require expensive appliance costs without incurring costs for the energy supply itself. The minimized total system cost in the model analysis process can lead to a sudden increase in the renewable share within a short period, an outcome unlikely to occur in the real world. Exogenous constraints are therefore added for the renewables under study. In CES, the shares of these renewables will not surpass the IEA's 450 scenario ([40]; Supplementary Table S4). Table 3 summarizes the definitions of the two scenarios.

Table 3. Scenario definitions.

Scenario	Definition
Fix (FIX)	Technology efficiency fixed at the 2010 level
Cost-effective selection (CES)	Efficient technologies naturally penetrated in the future market Share of non-commercial energy not to surpass the 2010 level Share of renewable energy not to surpass the IEA's 450 scenario

3. Results and Discussion

3.1. Energy Service Demands

Figure 6 shows the energy service demand of the whole of China and three Chinese regions with different urbanization levels. The urban and rural populations are disaggregated results from SSP2. The urban service demand is drawn from the results from our previous study [22]. Beijing and Tibet represent high and low urbanization cases, respectively. Different factors drive constant increases in the rural service demand in Beijing and Tibet. The share of the rural population in Beijing drops considerably by 2050, but the rural population grows in absolute terms because the total Beijing population doubles. The rural energy service demand thus increases intensively due to increases in both the population and income level. Tibet currently has the highest rural population share and is expected to keep this rank in 2050. The increase of the rural energy service demand in Tibet probably stems from the slow but steady process of urbanization and rising income. Inner Mongolia represents a middle urbanization case. As income rises and the rural population falls, rural energy service demand in Inner Mongolia grows up to 2030, then declines over the next two decades. The same pattern is observed when aggregating all 31 regions into China's national results.

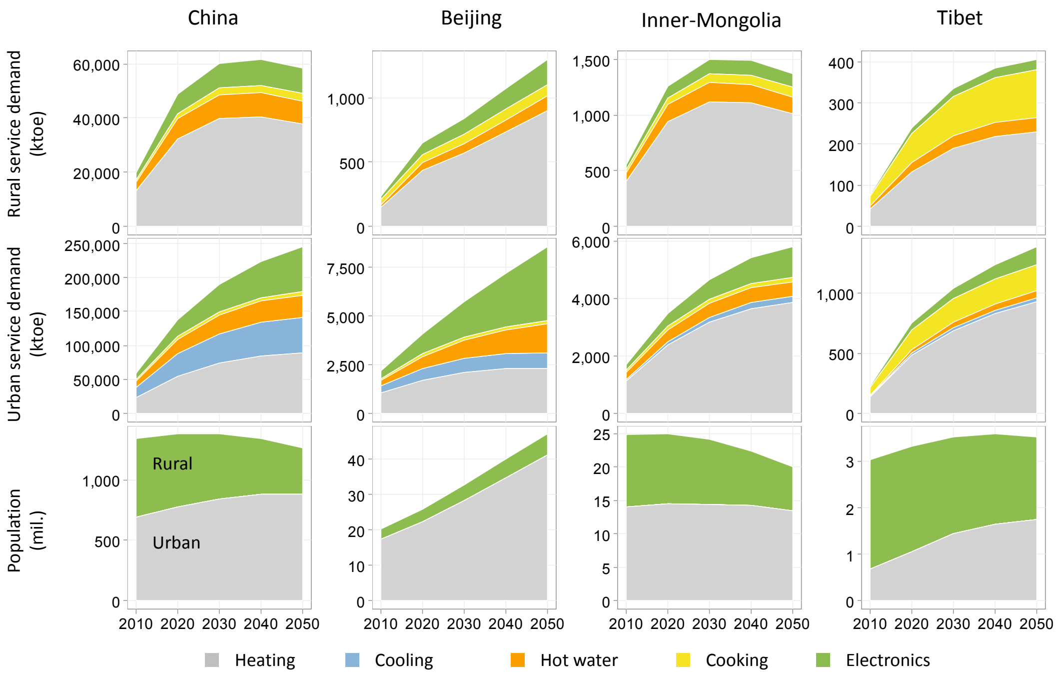

Figure 6. Energy service demand of 31 Chinese provinces in SSP2.

3.2. Energy Consumption and CO_2 Emission

Figure 7 shows the estimated results of energy consumption (top row) and CO_2 emissions (bottom row) in China's rural households. We selected four representative regions with different building codes and looked into their future projections. Overall, energy consumption and CO_2 emissions both grow drastically in the future. In CES, efficient technologies penetrate the market—in some cases in limited amounts—even without emission taxes or technology subsidies. In the target year (2050), the FIX-compared reduction rate ((FIX-CES)/FIX) of energy consumption appears to be low in cold regions (6% in Heilongjiang, China) and high in warm regions (19% in Guangdong, China). Reductions in the consumption of coal and electricity energy contribute the bulk of the CO_2 emission reductions. The FIX-compared reduction rate of CO_2 emissions in the target year ranges from 21% in cold regions (Heilongjiang, China) to 54% in warm regions (Guangdong, China). Electricity renewables (photovoltaic panels, *etc.*) have no observable reduction impact on the results. This tells us that the expensive upfront costs of electricity renewables will dissuade the regions from adopting them unless a carbon tax, technology subsidies, or other financial supports are provided.

Penetration of efficient technologies also has impacts on per capita energy/emission intensities. In Beijing, per capita energy consumption drops from 534.92 ktoe/cap (FIX) to 492.84 ktoe/cap (CES) while per capita CO_2 emissions drop from 105.98 tCO_2/cap (FIX) to 86.03 tCO_2/cap (CES) by 2050. In Guangdong, a warm region, per capita energy/emission intensities are much lower than Beijing's level. Nevertheless, there is a marked reduction of energy/emission intensities in CES. Per capita energy consumption drops from 105.98 ktoe/cap (FIX) to 86.03 ktoe/cap (CES) while per capita CO_2 emissions drop from 0.37 tCO_2/cap (FIX) to 0.17 tCO_2/cap (CES) by 2050. However, compared to the results of the urban residential sector from our previous study (Xing, 2015 [22]), per capita energy/emission intensities in rural households are much lower than in urban households. This indicates that even with efficient technologies, emission reduction will not be as substantial as that in urban households considering the future growth of the urban population.

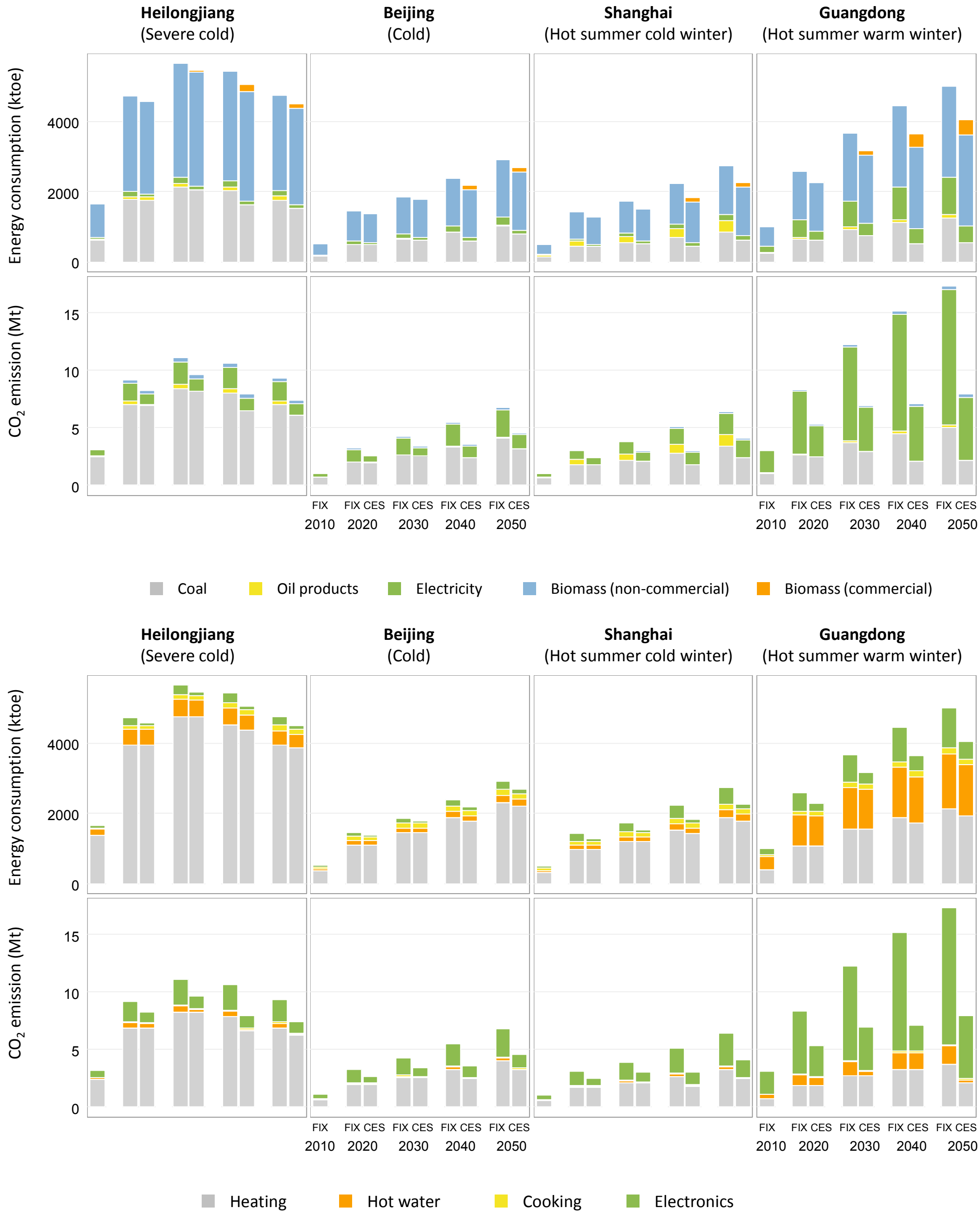

Figure 7. Energy consumption and CO_2 emissions of China's rural residential sector.

3.3. Technology Selection

In this study we provide a choice of 83 residential energy service (Table 2) technologies within the AIM/Enduse model to keep the cost as low as possible while attaining CO_2 emission reduction. Figure 8 shows the efficient technologies that bring about the greatest CO_2 emission reductions in four representative provincial areas. Although the reduction shares of each technology differ among the four regions, the technology selection seems to be unanimous: efficient lighting, biomass water heaters, and efficient electronics.

The diffusion of the fluorescent lamp contributes over half of the CO_2 emission reduction in all four regions. The fluorescent lamp and LED lamp are respectively considered a "NEW" lighting technology and an optimally efficient "BAT" technology in this category. Nevertheless, the model simulation results suggest a large penetration of the fluorescent lamp with no accompanying penetration of LED. Though less efficient than LED, the fluorescent lamp has the appealing advantage of an affordable price. The fluorescent lamp can thus be seen as a bridge between the traditional incandescent lamp and LED, especially in rural households. Biomass (wood residuals) is considered a carbon-neutral energy source important for CO_2 emission reduction. The biomass water heater ranks as the second most important technology in Heilongjiang and Guangdong, and the third most important in Beijing and Shanghai.

No emission tax or technology subsidy is included in the low-carbon scenario of this study. We examine only the energy savings brought about by efficient technologies. This necessarily limits the selectable technologies. In future studies we will also consider financial instruments when we design our scenarios. We also expect regions to adopt different technology combinations best suited to their respective climates and economies.

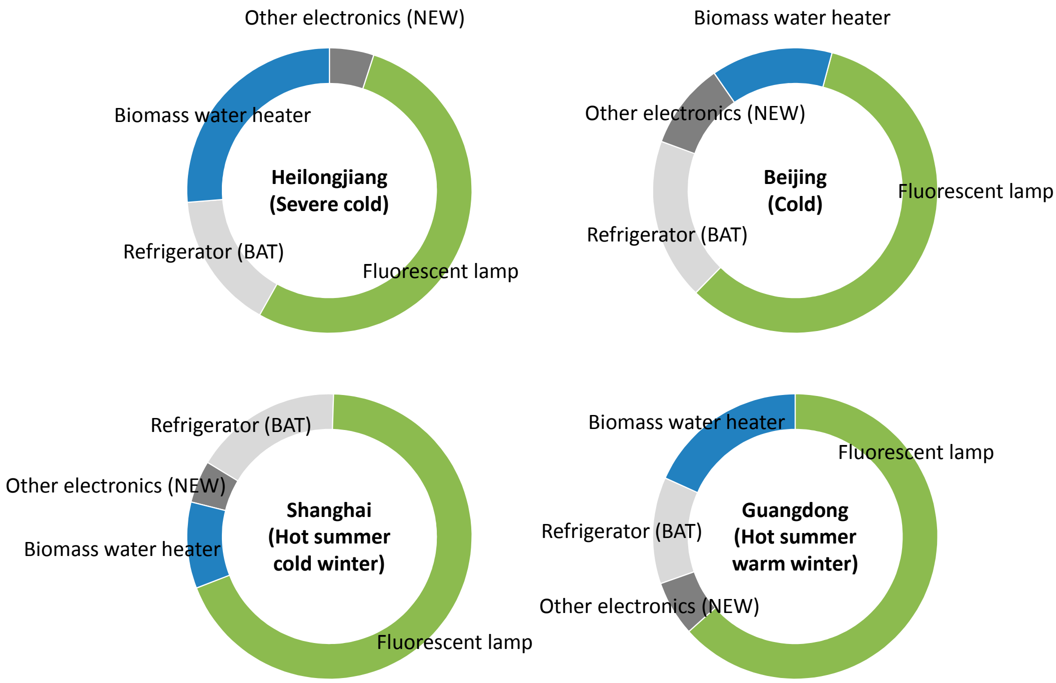

Figure 8. CO_2 emission reduction contributors in four provincial areas.

4. Conclusions and Future Work

4.1. Conclusions

This study highlights the importance of considering the socio-economic and climate diversity that exist across rural areas in China while estimating the rural energy demand. Future energy demand in rural households is estimated using a well-grounded methodology. The results show that energy service demand in China's rural household sector will continue to increase in regions with growing population or income conditions. In most Chinese regions, the rural service demand will start to decline after 2030. The results show that the decoupling between energy and emission is higher in warm areas compared to cold areas in rural households. Compared to our previous study [22] related to urban household energy demand estimation, emission intensity improvement is lower in rural households in the competitive technologies selection scenario. The results indicate that the technology transition can achieve emission reductions in the rural area in an efficient manner without any financial stimulus such as tax or subsidies. For example, for the lighting service, a switch happens towards the moderate technology such as fluorescent lamps in terms of both cost and energy efficiency. The key contribution of this study is to estimate the rural household energy demand at the provincial level which helps bring out the comparative dynamics between the warm and cold regions of China. For instance, the CO_2 reduction potential ranges from 20% to 50% across all 31 regions and appears to be relatively larger in warm areas than in cold areas. Yet without certain policies in place, the diffusion of efficient technologies will be limited. Efficient lighting, biomass water heaters, and efficient electronics bring about the greatest benefits in rural households.

4.2. Future Work

Future studies should be carried on the following aspects. First, due to limited data related to non-commercial biomass, the maximum share of non-commercial biomass in this study is manually fixed in future scenarios. Field surveys could provide more insights related to fuel-switching dynamics in the China's rural household sector. This would help to assess the impact of income growth on energy structure in the household sector in rural areas. Second, this study focuses solely on the residential sector under the assumption that all 31 provinces use a national electricity grid. As such, an average emission factor for electricity is applied for all 31 provinces, and this value is fixed in the future in order to evaluate impact from the demand side only. To understand the impact of regional dynamics in a comprehensive manner, future study is required linking demand and supply sides at the regional level. Third, according to the empirical studies [2,5,6,24], cooling services are not widely used in the Chinese rural household. This study extends the current situation into the future and excludes the cooling services. Future studies can consider the possibility of using cooling services by designing other scenarios. For instance, for the cold regions in China, insulation retrofitting can be an efficient way to reduce the energy demand and CO_2 emissions. However, due to data unavailability related to the technical details and deployment share of insulation retrofit technology, the technology is not included in the current study. Further research is required to be conducted for marking the profile of the insulation level in rural residential buildings in order to assess the impact from insulation retrofitting on the energy profile of the rural household sector. Last but not least, in this study the projections of all socioeconomic indicators are limited with SSP2's "business-as-usual" storyline. For instance, projections of floor space and white/brown goods' ownership are extrapolations of historical panel data, which implies a stable development in the rural households. Further research should be undertaken to account for the all the uncertainties related to the socio-economic indicators to have a better understanding of the rural energy sector dynamics.

Note

1. The rural areas mentioned in this study are the national administrative divisions treated as "rural areas" in the "China Statistical Yearbook" [41].

2. The working power of a refrigerator is an average value of refrigerator models that are commonly used in China's rural families (108L-298L).

3. Only socioeconomic projections (total population, urban population share and per capita GDP) from SSP2 are considered. Mitigation or adaptation projections in SSPs are not taken into account in scenarios of this study.

Supplementary Materials: Figure S1: China's climate zones; Table S1: Regional residential floor area (rural, million m^2); Table S2: Ownerships of household electronics (unit/household); Table S3: List of technologies considered in the AIM/Enduse model; Table S4: Building energy demand (China, 450 Scenario) [40]; File S1: Disaggregation of socioeconomic indicators [22]; File S2: Regression analysis of per capita floor area; Table S5: Coefficients of per capita floor area; Table S6: Electricity emission factor in Enduse/Global [38].

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