China Economic Review 78 (2023) 101917

Contents lists available at ScienceDirect

China Economic Review

journal homepage: www.elsevier.com/locate/chieco

Residential responses to service-specific electricity demand: Case of China

Jun-Jun Jia [a], Jinlan Ni [b,*], Chu Wei [c,**]

[a] School of Economics, Hefei University of Technology, Hefei 230601, PR China
[b] Milgard School of Business, University of Washington, Tacoma 98402, United States
[c] School of Applied Economics, Renmin University of China, Beijing 100872, PR China

ARTICLE INFO

JEL code:
C31
D12
J11
Q41

Keywords:
Chinese residential sector
Service-specific electricity consumption
Socioeconomic determinants
Heterogeneous responses
Conditional demand analysis

ABSTRACT

Understanding the diversity of the residential demand for various electrical services is critical for utilities and policymakers in conducting effective demand side management and narrowing urban-rural inequality. Previous research has usually treated the household as a unit of analysis, and thus may have ignored the fact that household electricity consumption is derived demand driven by specific services, which fails to examine the heterogeneous behavioral responses. Therefore, this paper presents a new pattern of residential demand for various electrical services and quantifies the impacts of socioeconomic determinants in China. The conditional demand analysis is performed on the unique dataset of the Chinese Residential Energy Consumption Survey of 2014 to estimate the electricity demand distribution in eight types of services and to investigate the effect of socioeconomic variables on service-specific electricity consumption. The results show that, together, entertainment and food refrigeration account for about half of the total annual electricity consumption, followed by laundry, lighting, space cooling, and hot water. Rural households use about 7.2% of total electricity for cooking purposes, while urban counterparts hardly use electricity to cook at all. Electricity consumption for space heating is negligible for both urban and rural households. Heterogeneity in socioeconomic determinants is found not only among different electrical services but also between urban and rural households.

1. Introduction

Residential electricity consumption is becoming increasingly important for global decision-makers under the sustainability constraint, especially because we are confronted with the 2-degree Celsius limit agreed upon in the Paris Agreement (Duan et al., 2021). The residential sector worldwide consumed around 27% of the total final electricity demand in 2018 (International Energy Agency, 2020). Thus, it constitutes a significant topic to examine residents' electricity-consuming behavior and form effective demand side management policies, both to alleviate energy shortages and to reduce the pollutant discharge and massive CO_2 emissions caused by electricity generation.

Previous studies have made great efforts in residential electricity demand analysis by utilizing sectoral statistics data in certain

* Correspondence to: Jinlan Ni, Milgard School of Business, University of Washington, Tacoma, WA, United States.
** Correspondence to: Chu Wei, School of Applied Economics, Renmin University of China, No.59 Zhongguancun Street, Haidian District, Beijing 100872, PR China.
E-mail addresses: jiajunjun@hfut.edu.cn (J.-J. Jia), Jni8@uw.edu (J. Ni), xiaochu@ruc.edu.cn (C. Wei).

https://doi.org/10.1016/j.chieco.2023.101917
Received 3 August 2022; Received in revised form 30 December 2022; Accepted 2 January 2023
Available online 4 January 2023
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regions or nations. For instance, Kamerschen and Porter (2004) estimated annual residential electricity demand function by using simultaneous equation models from 1973 to 1998 in the U.S.; Halicioglu (2007) estimated the short-run and long-run income and price elasticities of the residential energy demand over the period 1968–2005 in Turkey; Auffhammer and Wolfram (2014) used province-level data for rural households to show that population share above the poverty line was an important determinant of household appliance holdings in China. Benefiting from recent microdata, studies have emerged using household surveyed or metered electricity consumption data to estimate price elasticity and income elasticity (Bernard, Bolduc, & Yameogo, 2011; Cao, Ho, Li, Newell, & Pizer, 2019; Hung & Huang, 2015; Jia, Guo, & Wei, 2021; Reiss & White, 2005), to assess how residents respond to demand side management policies (Muratori, 2018; Rapson, 2014; Wolak, 2011), and to help scholars better understand how different socioeconomic variables, dwelling characteristics, and climatic conditions affect electricity use (Brounen, Kok, & Quigley, 2012; Li, Pizer, & Wu, 2019; Ruijven, Cian, & Wing, 2019). However, specific demand patterns of electrical services within the household have not been explored. In addition, the household level data may mask the heterogeneity in consumption behaviors, as the implicit assumption has been that socioeconomic factors have the same effect on all end uses of electricity.

Therefore, it is important to switch from household-based analysis to service-oriented study for the following reasons. **First**, the composition of household electricity consumption constitutes an important dimension to measure family welfare and becomes a key indicator to represent service flows and monitor welfare changes (Wu, Zheng, & Wei, 2017). Unlike aggregate household electricity consumption, the detailed composition of electrical services can reflect a change in family welfare even though the aggregate consumption does not change (Dubin & McFadden, 1984; Quigley, 1984). **Second**, ignoring the heterogeneous effects of socioeconomic variables on demand for different electrical services may seriously misguide policy formulation. China is experiencing a long-term process of aging, shrinking family size, fewer children, improvement of education level and family income (Han, Wei, & Cao, 2022; National Bureau of Statistics of China, 2021). Revealing the heterogeneous impacts of these socioeconomic variables on different electrical services can guide policies to focus on the end uses that are experiencing significant changes in power demand, and to formulate precise responses in a more cost-effective policy mix. For instance, existing studies have estimated income elasticity of total electricity consumption. However, they tend to ignore the potential heterogeneous impacts of the income variable on different electrical services (e.g., space cooling/heating has larger income elasticity than lighting). Accordingly, policy makers should focus on policies to change electricity consumption in specific services (say, space heating), such as implementing replacement subsidies to improve energy efficiency for specific services (say, adopting new heating modes) instead of adopting a one-size-fits-all approach to improve the energy efficiency of all electrical appliances. The existing studies are unable to tackle this issue by using total electrical demand.

Our study echoes the call for research into electricity demand at the end-use level, to better understand residential consumption habits and behavior patterns (Kelly & Knottenbelt, 2015), to assist utilities in designing better demand response of energy generation to improve the security of the power grid (Monacchi, Egarter, Elmenreich, D'Alessandro, & Tonello, 2014), and to guide policymakers in targeting instrument design for demand side management (Newsham & Donnelly, 2013). We present the demand pattern covering eight types of electrical services by using a unique nation-wide household survey data in China. Furthermore, we quantify the heterogeneous impacts of socioeconomic variables on different service-specific electricity demand. The results indicate that household electricity demand from entertainment and food refrigeration services makes up around half of the total annual consumption. The services of laundry, lighting, space cooling, and hot water constitute smaller shares. About 7.2% of total electricity is used for cooking purposes by rural households, with urban counterparts hardly using electricity to cook. Negligible electricity is used for space heating by both urban and rural households. The heterogeneity in socioeconomic determinants is unveiled not only among different electrical services but also between urban and rural households. Individual characteristics of household heads have significant impacts in rural areas, while family composition shows significant impacts in urban areas. Household income level is associated with differential electricity-consuming behaviors in multiple services, with differences between urban and rural households.

Our paper contributes to the existing literature in three aspects. **First**, to the best our knowledge, the paper is the first one that disaggregates household total electricity consumption into the service-specific level in China. This helps us better understand the electricity end-use distribution and link it to residential consumption habits and behavior patterns. **Second**, we further investigate how household socioeconomic variables disparately affect service-specific electricity use. This service-level electricity consumption information can serve as the reference to forecast household electricity demand by specific household socioeconomic status. **Third**, the estimated service-level electricity consumption helps identify daily activities with high energy-saving potential and provides data support for investigating the inequality of residential electricity consumption among different groups.

The rest of paper is organized as follows. Section 2 briefly introduces the residential electricity consumption and the urban-rural disparity in China. Section 3 introduces the survey data, data processing, and the conditional demand analysis model. Section 4 presents household characteristics, socioeconomic impacts on electrical services, and the heterogeneous analysis between urban and rural households. Section 5 discusses the implications of the results for urban-rural inequality under carbon neutrality. Section 6 concludes.

2. Residential electricity consumption in China

We select China as our case for several reasons. First, because China is the largest energy consumer and top global CO_2 emitter, it will be difficult for the world to achieve the global energy transition and climate target without action by China. China has pledged that its CO_2 emissions will peak by 2030, and aims to achieve carbon neutrality by 2060. This calls for substantial effort from the residential sector, which is the second largest energy user in China. Second, wide-scale end-use electrification has been adopted as one prioritized strategy for climate resiliency. Third, China is experiencing not only tremendous growth of residential electricity consumption, but also a great disparity among different groups, i.e., the urban-rural gap. The growing, dynamic and heterogeneous setting of China provides a unique research window and contains lessons for other countries.

As shown in Fig. 1A, residential electricity consumption in China has grown more than tenfold over the last 25 years, from about 900 TWh in 1994 to almost 10,000 TWh in 2018, with an annual increase rate of about 10.6%. However, as most literature has confirmed, there is great disparity in terms of economic and social development between China's urban and rural areas (Yang, 2012). This wide urban-rural gap also holds for residential electricity consumption, which is associated with their respective living standards. Shown by the red dot-line in Fig. 1A, urban residents' electricity consumption was about 1.3–1.4 times higher than their rural counterparts from 2008 to 2017. This disparity declines overall, but with a rising trend in recent years.

Fig. 1B presents the family size and per capita disposable income gaps between urban and rural households. Although family size is continuously shrinking in both urban and rural areas due to the fertility policy, rural households have 3.9 persons on average, almost one person more than urban counterparts. Accordingly, while disposable income per capita has risen at an increasing rate in both urban and rural areas, the urban-rural gap has also increased.

Panels C and D in Fig. 1 show the urban-rural difference in home appliances ownership. Fig. 1C plots refrigerator ownership for urban and rural residents over time. It shows that rural households have an accelerated growth rate in refrigerator ownership and converge to the level of their urban counterparts. However, Fig. 1D shows a persistent and increasing gap in air-conditioner ownership between urban and rural areas, with the urban-rural difference in the air-conditioner penetration rate increasing from 1.2 units/100 household in 1993 to 76 units/100 household by 2017.

The significant disparity between urban and rural residents in China in Fig. 1 suggests that it is not enough to conduct household electrical services analysis without considering the heterogeneity between urban and rural households. Thus, comparing the difference between urban and rural household appliance-specific services and unveiling the heterogenous socioeconomic determinants constitute

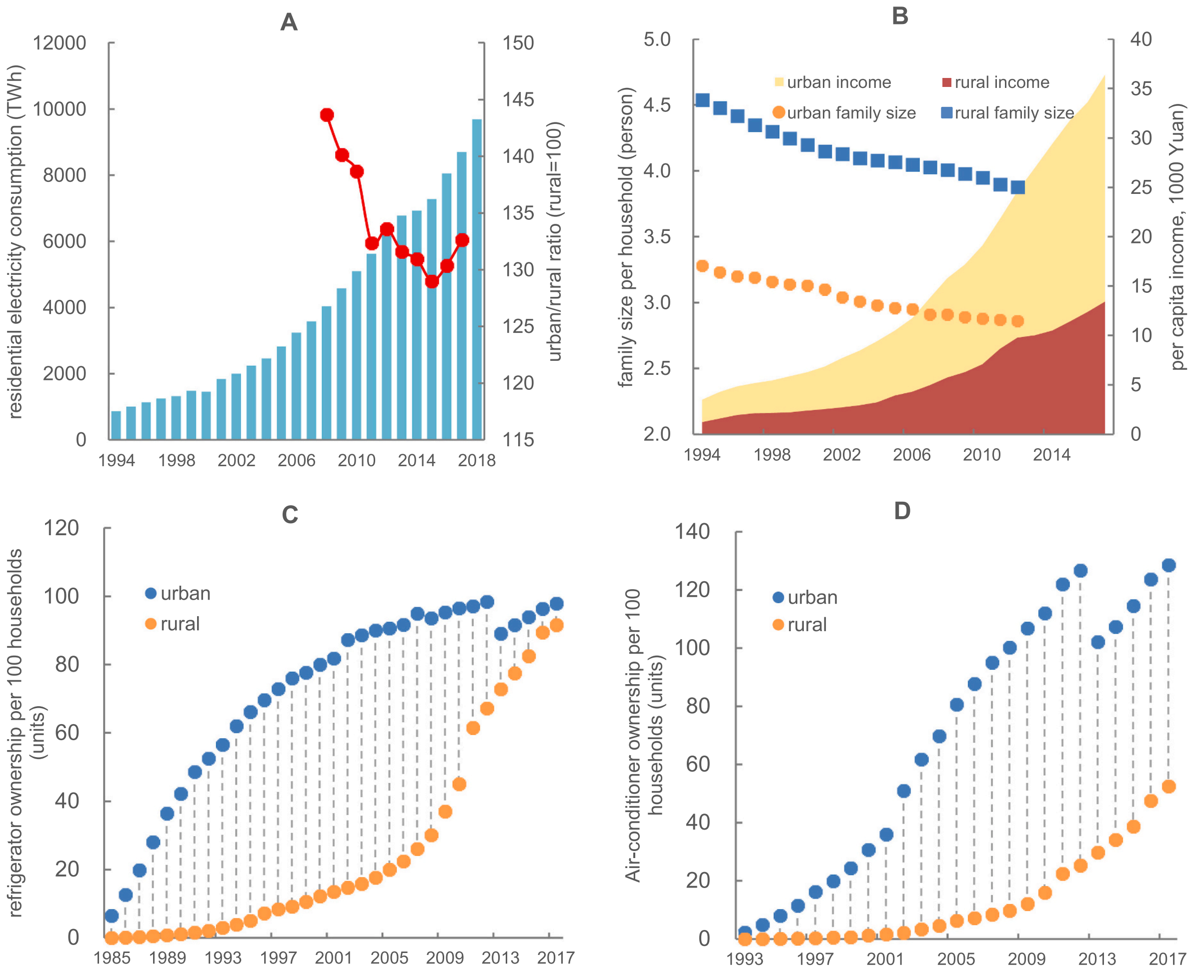

Fig. 1. Development of Chinese residential sector. A) electricity consumption and urban-rural gap; B) urban-rural difference in socioeconomic variables; C) urban-rural refrigerator ownership; D) urban-rural air-conditioner ownership.
Note: Data come from China Statistical Yearbook 2019.

a necessary step in our study.

3. Data and model

3.1. Survey data

We use household-level micro survey data, the Chinese Residential Energy Consumption Survey (CRECS), conducted by the Department of Energy Economics, Renmin University of China. It is the most comprehensive and detailed nation-wide household energy survey in China to date (Zheng & Wei, 2019). There have been six rounds of surveys since the year 2012. Here we select the CRECS 2014 for our analysis. The CRECS 2014 was conducted between July and October 2015 over 28 provinces of China to record the state of household energy consumption in 2014. The map-based sampling technique was adopted to ensure representativeness. The CRECS 2014 includes three major modules: the household routine and respondents' socioeconomic variables; reported energy consumption data (including electricity usage and other data in 2014); and in-depth detailed home appliances ownership information in each household (whether households having surveyed appliances or not). This unique data structure enables us to first determine ownership of eight electrical devices for every household and then disaggregate the household-level electricity consumption data to our desired service clusters. A total of 3864 questionnaires were issued and the 2408 completed samples were collected at the end. The sample retrieval rate is 62.3%. After taking out outliers in terms of household income and family size, there remain 2402 observations in total for analysis.

3.2. Classification of electrical services

There are 12 types of home appliances ownership recorded in CRECS 2014, which cover almost all electricity-consuming devices commonly used in a typical Chinese household. The appliances are categorized based on their service function, following three considerations. **First**, multiple appliances serving a common purpose will be classified into one category, although they are concurrently owned by a typical household. For example, electric rice cooker, induction cooker, pressure cooker, and microwave oven will be sorted into Cooking because they all serve the cooking purpose. **Second**, one type of electrical appliance has been sorted into two different services because it can provide different kinds of services. Take an air conditioner, for example. It can offer either space cooling service in summer or space heating service in winter. Thus, the two services are distinguished for air conditioners. **Third**, some types of electrical appliance can serve multiple purposes but only be sorted into one main function. For instance, the computer can be used for both work and entertainment. But according to recorded usage habits of respondents, most of the time they use the computer at home is for entertainment purposes. Thus, the computer is categorized into entertainment service, together with the television.

Table 1 distinguishes and categorizes eight types of electrical services based on the appliances' function. For each type of service, the household is marked as having the service if it owns any of the corresponding appliances. Otherwise, it is marked as having no such service. Total household electricity consumption is disaggregated into the listed eight services. We explore how each type of service responds to socioeconomic status.

3.3. Descriptive statistics

Table 2 presents descriptive statistics of socioeconomic status variables of the household, appliance service ownership, and household electricity consumption of the year 2014 for sampled Chinese households. As we can see, 52% of household heads are female, with average age around 55, and middle school education level on average. The average family size is 2.93 and average household annual income is around 58,219 Yuan. The average electricity consumption per household in 2014 is 1572 kWh. All these statistics are comparable to the China Statistical Yearbook 2015 (National Bureau of Statistics of China, 2015), which shows that, for 2014, the female ratio is 0.49, family size is 2.97, national average household income is 59.90 thousand Yuan, and average electricity consumption per household is 1505 kWh. This confirms the representativeness of the surveyed data.

Micro-household survey data in Table 2 reveals the significant disparity between urban and rural households, consistent with the facts displayed in Fig. 1 using sectoral macro aggregate statistic data. Specifically, the household head in urban areas tends to be older

Table 1
Electrical appliances and their corresponding services.

Services	Electrical appliances
Cooking	Electric rice cooker, Induction cooker, Pressure cooker, Microwave oven
Entertainment	Television, Computer
Food refrigeration	Refrigerator, Freezer
Hot water	Electric kettle, Electric water heater
Laundry	Washing machine, Dryer
Lighting	Lighting points
Space cooling	Air conditioner (cooling)[a]
Space heating	Air conditioner (heating)[a], Electric heater, Electric oil heater, Electric heating film

Note: [a] The air conditioner can be used for space cooling in summer and for space heating in winter. The two distinct services are distinguished in the study.

Table 2
Descriptive statistics (mean and standard deviations in parentheses).

Variables		Definition (Unit)	China	# urban	# rural	*p*-value
Socioeconomic variables	Head's gender	male = 0 female = 1	0.52 (0.50)	0.52 (0.50)	0.53 (0.50)	0.639
	Head's age	years	54.74 (16.07)	56.1 (16.63)	53.8 (15.60)	0.001
	Head's education	schooling years	8.55 (4.55)	10.74 (4.06)	6.99 (4.23)	0.000
	Household income	Yuan	58,219 (71920)	79,543 (86733)	42,879 (54066)	0.000
	Family size	persons	2.93 (1.36)	2.74 (1.23)	3.07 (1.42)	0.000
	Having teenagers	yes = 1 no = 0	0.29 (0.46)	0.24 (0.43)	0.33 (0.47)	0.000
Appliance services ownership[a]	Entertainment	have = 1 do not have = 0	0.97 (0.16)	0.99 (0.11)	0.96 (0.19)	0.001
	Food refrigeration		0.85 (0.36)	0.92 (0.27)	0.79 (0.41)	0.000
	Laundry		0.80 (0.40)	0.88 (0.32)	0.74 (0.44)	0.000
	Cooking		0.76 (0.42)	0.82 (0.38)	0.72 (0.45)	0.000
	Lighting[b]		0.55 (0.50)	0.58 (0.49)	0.53 (0.50)	0.007
	Space cooling		0.41 (0.49)	0.61 (0.49)	0.27 (0.44)	0.000
	Hot water		0.37 (0.48)	0.52 (0.50)	0.25 (0.44)	0.000
	Space heating		0.09 (0.28)	0.11 (0.31)	0.07 (0.25)	0.001
Electricity consumption in 2014		kWh	1572 (1325)	1919 (1506)	1323 (1114)	0.000
Sample size			2402	1005	1397	

Note: [a] Services are presented by mean ownership in descending order.
[b]Lighting is equal to 1 if the number of lights in one household outweighs 6, 0 otherwise, similarly hereinafter.

and better educated while rural households tend to have a larger family size and more children. It is worth noting that urban households are significantly more affluent and the average annual urban household income is about 1.86 times that of rural counterparts. Besides, the average electricity consumption of urban households is about 1.45 times that of rural households. In terms of appliance-specific service ownership, urban households have significantly higher shares compared to rural households in all listed eight services. The significant disparity between urban and rural areas suggests that it is pivotal to conduct urban-rural heterogeneity analysis in household consumption behavior of electrical services.

3.4. Conditional demand analysis model

Several methods have been developed to disaggregate household electricity consumption to electrical devices. These include the engineering method (Carlson, Matthews, & Bergés, 2013; Zheng & Wei, 2019) and signal processing technologies (Berges, Goldman, Matthews, Soibelman, & Anderson, 2011; Swan & Ugursal, 2009; Zeifman & Roth, 2011). Although there are some merits of these methods, they suffer from expensive costs for data monitoring and collection for specific devices. Moreover, they are incapable of capturing behavioral impacts of household characteristics on residential electricity consumption. Because the conditional demand analysis (CDA) model can overcome these two drawbacks, it has been widely used for residential electricity demand analysis for various developed countries (Larsen & Nesbakken, 2004; Matsumoto, 2016; Newsham & Donnelly, 2013).

The CDA model is used in the paper to decompose the household total electricity consumption into demand for various services and to simultaneously model the impacts of different socioeconomic variables. We first estimate the model using the whole sample and then proceed to do subgroup analysis in urban area vs. rural area.

The electricity consumption x_{ij} of the *i*-th household and *j*-th service can be estimated as follows (Dalen & Larsen, 2015).

$$x_{ij} = \gamma_j + \sum_{m=1}^{M} \rho_{jm} \left(C_{im} - \overline{C_{jm}} \right) + \varepsilon_{ij} \tag{1}$$

where γ_j is the average electricity consumption of service *j* for households possessing service *j*. C_{im} denotes the *m*-th ($m = 1,2, \ldots,M$) socioeconomic characteristic of household *i*. $\overline{C_{jm}}$ is the mean of the *m*-th socioeconomic characteristic of households having service *j*. The coefficient ρ_{jm} measures how the deviation of C_{im} from $\overline{C_{jm}}$ affects γ_j. ε_{ij} is the stochastic error term.

Each service-specific electricity consumption can be added up to obtain household aggregate electricity consumption. Then, by

Table 3
Estimated conditional demand model.

Variables	China			#Urban			#Rural		
	coef	*t*	p-value	coef	*t*	p-value	coef	*t*	p-value
Entertainment	492.094	5.400	0.000	617.560	2.811	0.005	474.028	4.658	0.000
**Gender*	98.762	0.635	0.526	29.715	0.077	0.939	203.942	1.311	0.190
**Age*	−4.763	−0.78	0.436	−0.214	−0.016	0.988	−3.781	−0.588	0.557
**Educational level*	3.338	0.163	0.871	−27.052	−0.512	0.609	6.510	0.285	0.776
**Household income*	−0.003	−1.725	0.085	0.002	0.404	0.686	−0.004	−2.350	0.019
**Family size*	−21.680	−0.374	0.708	−320.422	−2.342	0.019	88.519	1.514	0.130
**Having teenagers*	−37.956	−0.189	0.850	311.819	0.589	0.556	−119.171	−0.607	0.544
Food refrigeration	366.859	3.870	0.000	370.216	1.702	0.089	325.730	3.122	0.002
**Gender*	81.561	0.516	0.606	−53.780	−0.135	0.892	92.987	0.606	0.545
**Age*	−1.184	−0.188	0.851	−11.927	−0.860	0.390	−0.109	−0.017	0.987
**Educational level*	37.414	1.729	0.084	12.139	0.218	0.827	45.142	2.028	0.043
**Household income*	0.001	0.286	0.775	−0.002	−0.380	0.704	−0.001	−0.339	0.734
**Family size*	2.041	0.035	0.972	86.138	0.545	0.586	16.263	0.282	0.778
**Having teenagers*	−212.346	−1.093	0.274	−557.787	−1.039	0.299	−202.374	−1.098	0.272
Laundry	259.153	3.371	0.001	338.288	1.859	0.063	170.191	1.927	0.054
**Gender*	−77.743	−0.560	0.576	−160.096	−0.491	0.623	−67.416	−0.487	0.627
**Age*	−0.018	−0.003	0.998	−0.463	−0.038	0.970	−0.028	−0.005	0.996
**Educational level*	−0.368	−0.020	0.984	4.694	0.101	0.919	−15.734	−0.790	0.430
**Household income*	0.003	2.619	0.009	0.004	1.556	0.120	0.003	2.154	0.031
**Family size*	73.055	1.378	0.168	121.269	0.903	0.367	41.224	0.784	0.433
**Having teenagers*	85.771	0.479	0.632	−3.849	−0.008	0.994	244.523	1.396	0.163
Cooking	97.796	1.645	0.100	20.641	0.147	0.883	131.866	1.681	0.093
**Gender*	83.871	0.698	0.485	256.391	1.087	0.277	−21.437	−0.165	0.869
**Age*	3.748	0.817	0.414	3.455	0.424	0.671	6.033	1.075	0.283
**Educational level*	−0.751	−0.047	0.963	59.386	1.654	0.098	−9.650	−0.505	0.614
**Household income*	0.000	0.435	0.663	−0.003	−1.502	0.134	0.001	0.883	0.377
**Family size*	8.774	0.196	0.845	206.111	2.154	0.031	−75.784	−1.635	0.102
**Having teenagers*	188.412	1.270	0.204	73.633	0.239	0.811	217.942	0.391	0.165
Lighting	257.731	5.005	0.000	225.666	2.008	0.045	354.286	5.076	0.000
**Gender*	−283.601	−2.750	0.006	−136.761	−0.719	0.472	−368.208	−3.168	0.002
**Age*	5.177	1.334	0.182	15.142	2.201	0.028	−0.242	−0.050	0.961
**Educational level*	−1.492	−0.110	0.912	17.172	0.603	0.547	−6.980	−0.415	0.678
**Household income*	0.000	−0.356	0.722	−0.002	−1.894	0.059	0.003	2.175	0.030
**Family size*	84.245	2.072	0.038	183.345	2.227	0.026	41.848	0.972	0.331
**Having teenagers*	−33.876	−0.270	0.787	96.998	0.407	0.684	−161.945	−1.165	0.244
Space cooling	474.761	7.550	0.000	500.062	4.585	0.000	309.708	3.194	0.001
**Gender*	−73.225	−0.666	0.505	108.397	0.544	0.586	−239.215	−1.778	0.076
**Age*	1.077	0.258	0.796	3.303	0.453	0.651	−12.111	−2.078	0.038
**Educational level*	−1.288	−0.086	0.931	−16.684	−0.566	0.572	−30.668	−1.543	0.123
**Household income*	−0.002	−1.666	0.096	−0.001	−0.984	0.326	0.000	−0.318	0.751
**Family size*	176.998	4.189	0.000	265.385	3.205	0.001	56.088	1.168	0.243
**Having teenagers*	−68.367	−0.513	0.608	−73.424	−0.289	0.772	56.986	0.360	0.719
Hot water	376.816	6.786	0.000	343.999	3.490	0.001	310.971	3.495	0.000
**Gender*	−27.841	−0.259	0.796	−56.331	−0.306	0.760	−74.393	−0.561	0.575
**Age*	2.776	0.703	0.482	3.992	0.607	0.544	−3.641	−0.635	0.526
**Educational level*	−35.595	−2.464	0.014	−48.176	−1.718	0.086	−35.341	−1.803	0.072
**Household income*	0.003	3.443	0.001	0.004	3.149	0.002	0.003	1.839	0.066
**Family size*	−37.480	−0.886	0.376	−54.069	−0.686	0.493	−68.498	−1.411	0.159
**Having teenagers*	275.795	2.138	0.033	140.261	0.604	0.546	457.069	2.970	0.003
Space heating	194.198	2.211	0.027	228.191	1.335	0.182	254.664	1.785	0.075
**Gender*	216.499	1.215	0.224	166.199	0.573	0.567	359.988	1.616	0.106
**Age*	11.335	1.706	0.088	12.059	1.110	0.267	15.329	1.460	0.145
**Educational level*	53.324	2.086	0.037	27.461	0.535	0.593	78.432	2.216	0.027
**Household income*	0.001	1.245	0.213	0.003	1.795	0.073	−0.001	−0.636	0.525
**Family size*	106.477	1.407	0.159	217.419	1.679	0.093	−8.680	−0.096	0.924
**Having teenagers*	17.196	0.083	0.934	−45.111	−0.126	0.899	122.831	0.477	0.634
R^2	0.673			0.683			0.674		
F-statistic	89.289***			39.660***			52.491***		

Note: All F-statistic are significant at the 1% significance level.

introducing a dummy variable D_{ij} that indicates whether households have a specific service, the total electricity consumption x_i of household i can be written as:

$$x_i \equiv \sum_{j=CO}^{SH} x_{ij} D_{ij} = \sum_{j=CO}^{SH} \gamma_j D_{ij} + \sum_{j=CO}^{SH} \sum_{m=1}^{M} \rho_{jm} \left(C_{im} - \overline{C_{jm}} \right) D_{ij} + \varepsilon_{ij} D_{ij} \tag{2}$$

Eq. (2) is the specification to be estimated by using ordinary least squares. γ_j and ρ_{jm} are parameters to be estimated. The predicted expected electricity consumption for service k can be calculated as mean electricity consumption for service k multiplied by the proportion of households possessing service k:

$$x_k^P = \widehat{\gamma}_k \overline{D_k} \tag{3}$$

The share of electricity consumption for service k is calculated by x_k^P divided by the mean observed electricity consumption for all households in our sample.

$$a_k^P = \frac{x_k^P}{\overline{x}} \tag{4}$$

The detailed results are summarized in Table 3, which reports the overall results and subgroup analysis for urban and rural areas. Section 4 will discuss the results in detail.

4. Results and discussion

4.1. Profile of household electrical services

Our estimation first yields the overall coefficients for eight electrical services as seen in Table 3. These estimated coefficients, combined with the ownership information, can be translated into the average electricity consumption for various electrical services listed in Table 4.

To explain the results in Table 4 more intuitively, Panel A of Fig. 2 plots an overall picture of the demand pattern of electrical services for a representative Chinese household that consumed 1572 kWh in 2014. Among all eight electrical services, entertainment activity amounts to about 477 kWh per year, or 1.31 kWh per day, accounting for about 30% of electricity consumption. Food refrigeration is the second largest electrical usage demand. It takes 312 kWh per year (or 0.85 kWh per day) and accounts for 20% of electricity demand. The third largest is for laundry service, which accounts for around 13% of electricity consumption. It is followed by space cooling (12%), lighting (9%) and hot water (9%). Although cooking is a traditional daily routine for Chinese households, it seems

Table 4
Average electricity consumption of each service.

Service types		(1) estimated coefficients	(2) ownership	(3) = (1)*(2) average electricity consumption (kWh)	(4) percent (%)
China	*Entertainment*	492.094	0.97	477	30.36
	Food refrigeration	366.859	0.85	312	19.83
	Laundry	259.153	0.80	207	13.19
	Cooking	97.796	0.76	74	4.73
	Lighting	257.731	0.55	142	9.02
	Space cooling	474.761	0.41	195	12.38
	Hot water	376.816	0.37	139	8.87
	Space heating	194.198	0.09	17	1.11
Urban	*Entertainment*	617.560	0.99	611	31.86
	Food refrigeration	370.216	0.92	341	17.75
	Laundry	338.288	0.88	298	15.51
	Cooking	20.641	0.82	17	0.88
	Lighting	225.666	0.58	131	6.82
	Space cooling	500.062	0.61	305	15.90
	Hot water	343.999	0.52	179	9.32
	Space heating	228.191	0.11	25	1.31
Rural	*Entertainment*	474.028	0.96	455	34.40
	Food refrigeration	325.730	0.79	257	19.45
	Laundry	170.191	0.74	126	9.52
	Cooking	131.866	0.72	95	7.18
	Lighting	354.286	0.53	188	14.19
	Space cooling	309.708	0.27	84	6.32
	Hot water	310.971	0.25	78	5.88
	Space heating	254.664	0.07	18	1.35

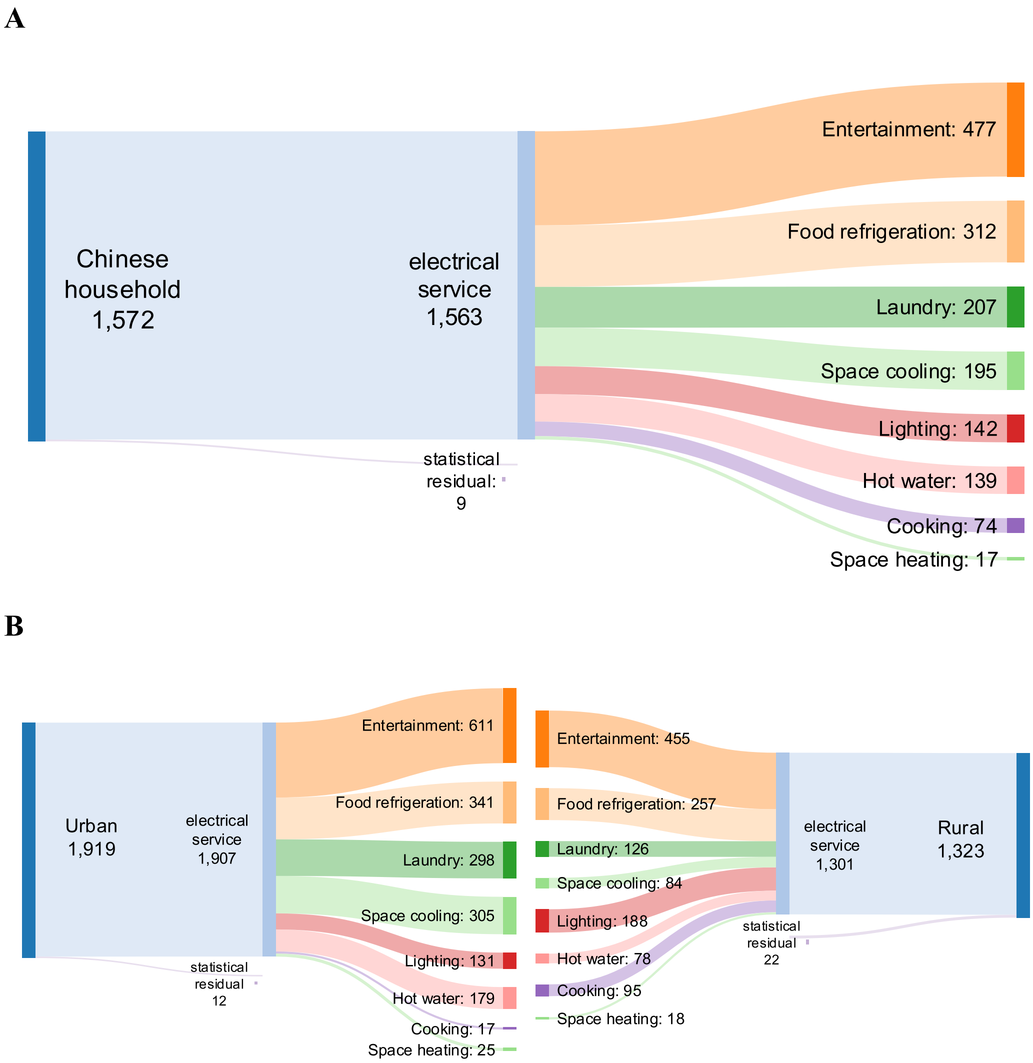

Fig. 2. Profile of electrical services flow chart (unit: kWh). A) for a representative Chinese household; B) for a representative urban and rural household.

that the electricity penetration in cooking activities is relatively low. The cooking-related electricity consumption is only 74 kWh (or 0.20 kWh per day) across all households, which accounts for a small percentage of 5%. In addition, only about 1% of electricity is used for space heating. This is probably due to the wide coverage of district heating systems for northern urban residents (Guo, Huang, & Wei, 2015).

Panel B of Figs. 2 demonstrates the urban-rural disparity of household demand for electrical services. Overall, urban residents have greater demand than rural households in terms of major electrical services, except for cooking and lighting services. On average, urban households consume 1919 kWh of electricity to meet their demand, which is 45% higher than rural residents (1323 kWh). For urban households, four types of end-use activities (entertainment, food refrigeration, space cooling and laundry) account for more than 80% of total electricity demand. As for rural residents, the demand for four end-use purposes (entertainment, food refrigeration, lighting and laundry) contributes 78% of total electricity usage. Another noticeable difference is the demand for space cooling services. For simplicity, assume there is a uniform three-month summer cooling period, and that the power needed for an air conditioner is 1 kW for both urban and rural households. Then the urban household would use 305 kWh (equivalent to 3.39 kWh per day, or 3.39 cooling hours per day) for space cooling, accounting for 15.9% of total electricity consumption. But the rural residents would only use 84 kWh (translating to 0.93 kWh per day or 0.93 cooling hours per day) for cooling purposes, which accounts for 6.3% of their electricity consumption. Furthermore, the significant difference in electricity usage is affected by lifestyle and alternative resources. For example, urban households consume about 2.3 times more electricity than rural counterparts in terms of laundry (298 vs 126 kWh/year) and hot water services (179 vs 78 kWh/year).

4.2. Socioeconomic impacts on electrical services

Table 3 also summarizes the effects of six socioeconomic variables on electricity demand for the eight electrical services, which are derived from the interaction items in the CDA model. Correspondingly, Fig. 3 presents graphically the heterogeneous socioeconomic effects on each service. Specifically, higher household income significantly pushes up electricity demand for laundry service. As with lighting service, females tend to exhibit better electricity-saving behavior than males. In addition, the larger the family size, the more electricity is needed for lighting. The positive significant relationship of family size also holds for space cooling. For hot water, more affluent households and households with teenagers tend to consume more electricity, while having a household head with higher education significantly lowers the demand for this purpose. This may be related to the bathing needs of occupations with different degrees of physical movement. Finally, we do see better-educated owners using more electricity for space heating. Nationwide, electrical services for entertainment, food refrigeration, and cooking are not significantly impacted by socioeconomic variables.

4.3. Urban-rural heterogeneity in socioeconomic impacts

We further distinguish the heterogeneous effects of socioeconomic variables on electrical services by urban and rural area. This helps us better understand the major driving forces and precisely identify intervention targets. The results are illustrated in Fig. 4 (also reported in Table 3).

Regarding socioeconomic determinants of electricity demand for services, obvious heterogeneity can be found between urban and rural households. Overall, individual characteristics of household head (gender, age, and educational level) have significant impacts mainly in rural households, while family composition (family size and having teenagers or not) has impacts mainly in urban households. The impact of the household income variable, on both urban and rural households, is scattered and irregular.

In terms of entertainment services, the larger the family size, the less electricity is used by urban households on television or computer. The increase in family size may lead to more interaction between family members, correspondingly decreasing entertainment requirements from television or computer. In rural areas, household income has a significant negative impact on electricity demand for entertainment. This may result from different lifestyles related to wealth, in that rich families are more likely to afford the luxury of outdoor entertainment.

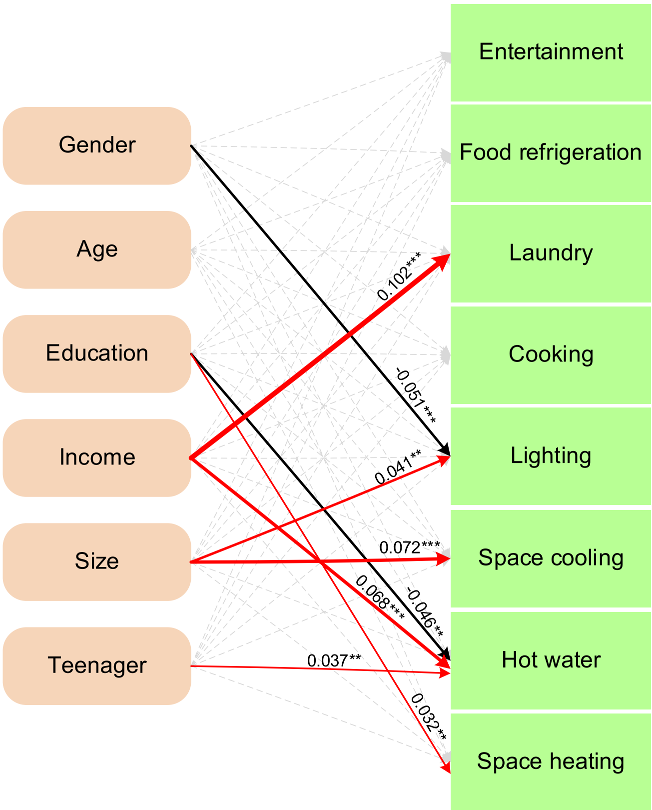

Fig. 3. Socioeconomic impacts on eight electrical services in China.
Note: The numbers in the figure are standardized coefficients. The red and black line indicates positive and negative correlation, while the thickness of the line indicates the effect size. ** and *** represent the 5% and 1% level of statistical significance, respectively.

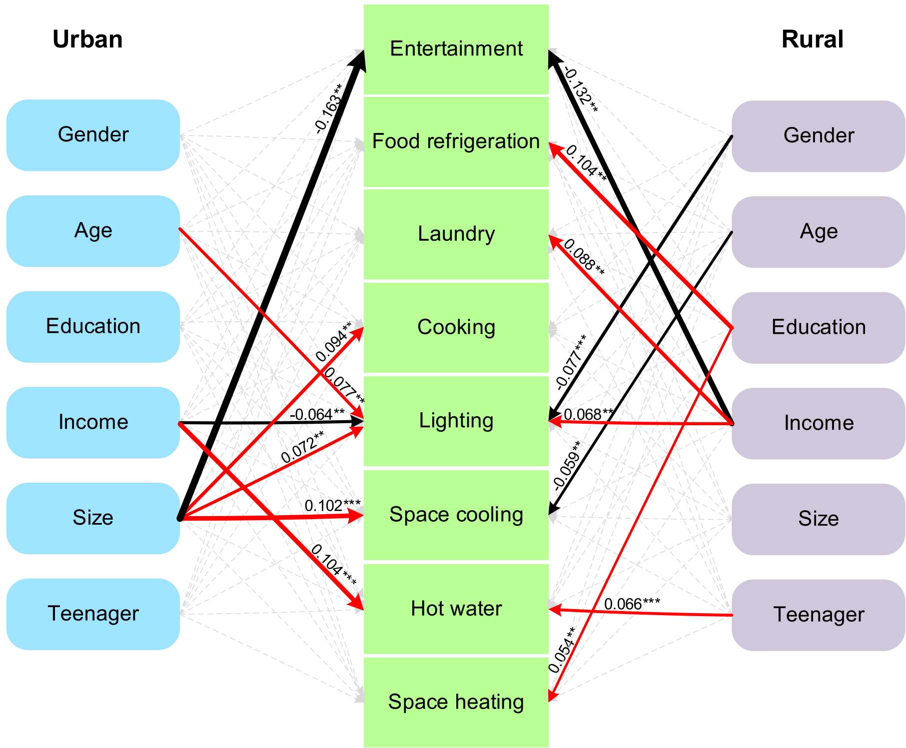

Fig. 4. Socioeconomic effects on eight electrical services by urban and rural area.
Note: The numbers in the figure are standardized coefficients. The red and black line indicates positive and negative correlation respectively, while the thickness of the line indicates the effect size. ** and *** represent the 5% and 1% level of statistical significance, respectively.

As for electrical services for food refrigeration, only in rural areas does the educational level of the household head have a positive significant impact on electricity demand. More years of education result in residents learning more about the importance of keeping food fresh, for purposes of health, and this probably drives electricity demand for refrigeration.

As for laundry services, only in rural areas does household income have a positive significant impact on electricity consumption. Higher income results in using a washing machine to replace the physical labor of hand-washing clothes.

Concerning electricity demand for cooking, more family members mean more frequent use of electrical devices for cooking, leading to significantly higher consumption of electricity by urban households.

With regard to lighting, in rural areas, females tend to have better electricity-saving habits than males. In urban areas, the younger the residents, the less electricity is consumed for lighting purposes. What's more, the larger the family size, the more electricity is consumed. Household income has opposite (and significant) impacts on urban households and rural households. This means that more affluent households and less affluent households, distinguished by mean household income, show different behaviors between urban and rural households in electricity demand for lighting. Specifically, in urban areas, the wealthier the household, the less electricity is consumed for lighting. But in rural areas, the wealthier the household, the more electricity is consumed for lighting. This suggests that rural households, with an increase of household income, are likely to increase their usage of lighting devices that are relatively inferior in terms of energy efficiency (such as kerosene lanterns), while urban households with increasing income reduce their electricity demand for lighting because of better access and affordability for more energy-efficient lighting devices.

Table 5
The ratio of eight service-specific electricity consumption.

	Urban	Rural	Urban-rural ratio
Space cooling	305	84	3.63
Laundry	298	126	2.37
Hot water	179	78	2.29
Space heating	25	18	1.39
Entertainment	611	455	1.34
Food refrigeration	341	257	1.33
Lighting	131	188	0.70
Cooking	17	95	0.18

Note: Electrical services are presented in descending order of urban-rural ratio.

With respect to space cooling services provided by an air conditioner, demographic variables have significant impacts on urban and rural households. In rural areas, the older the people, the less electricity is consumed. In urban areas, the larger the family size, the higher electricity demand for air conditioning.

As to electricity demand for hot water, having teenagers in rural areas pushes the demand for hot water up, probably due to a higher frequency of bathing. But only household income significantly increases electricity consumption for this purpose in urban areas.

Concerning electrical space heating, a household head with higher education is the only variable that increases electricity consumption for this purpose in rural areas, while no socioeconomic variables have a significant impact in urban areas.

5. Urban-rural inequality under carbon neutrality

Results in Section 4 reveals the inequality and heterogeneity of China's urban and rural household service-specific electricity consumption, which also enriches the knowledge of household carbon footprint inequality. Table 5 shows the ratio of electricity consumption in the eight services. First, there are significant differences between urban and rural households in the consumption of the eight services, which means that there is significant inequality in the urban-rural carbon footprint. Besides, services with high electricity consumption in urban households, namely ones with high carbon footprint, tend to provide life-improving services, such as space cooling, laundry and hot water. This is consistent with the conclusions of carbon footprint inequality between China's urban and rural households revealed by existing research, and our research is further detailed to the carbon footprint inequality of various electrical services (Shi, Wang, Cheong, & Zhang, 2020; Wang et al., 2022; Zhang et al., 2020).

Second, China is experiencing a long-term process of aging, shrinking family size, fewer children, improvement of education level and family income (Han et al., 2022; National Bureau of Statistics of China, 2021). This means that, on average, the variables of *age*, *education*, and *income* used in the paper will continue to increase, while the variables of *size* and *teenager* will continue to decrease. Combined with Fig. 4 displaying the heterogeneous determinants, the coarse forecast of net urban-rural ratio change can be summarized in Table 6. It shows that the ratio of electricity consumption in terms of hot water, entertainment and cooking services will further increase between urban and rural households in China, which means that carbon footprint inequality in these three services will be further widened.

Third, the unlocked electricity consumption among eight household electrical services would be a valuable input to make effective policy decisions to achieve carbon equity. Carbon pricing policies, such as the emissions trading system, are currently being implemented and are expected to be strengthened in the foreseeable future in the context of China's commitment to carbon peak by 2030 and carbon neutralization by 2060 (Zhang et al., 2022). However, based on the simulation results of Jia, Wen, and Liu (2022), all six scenarios of different carbon pricing policies would lead to more welfare loss in rural households and the urban-rural inequality would be further widened. In searching for an effective policy to narrow urban-rural inequality, they found that an individual tax cut based on household electricity consumption was promising. The decomposed electricity consumption among the eight services within one household in our study reflects the inequality of service-specific electricity demand. Thus, incorporating more detailed service-specific electricity consumption, instead of using household total electricity consumption, is likely to produce more penetrating insights and form more policy options to narrow the existing urban-rural inequality.

6. Conclusion

This paper estimates the electricity demand distribution of eight appliance-services and investigates how socioeconomic variables affect electricity demand of each service, by using the unique household-level dataset of the Chinese Residential Energy Consumption Survey 2014. Specifically, we report quantitatively household electricity demand composition across appliance-services and identify the impact of socioeconomic variables on each of electrical services. Further, we conduct sub-group analysis of urban and rural areas to uncover the similarities and heterogeneity for precise policy formulation. These findings have important policy implications to conduct household electricity demand side management and subsequently to reach the goal of CO_2 reduction in China.

First, government policy should focus on the anticipated surge in household total electricity consumption, especially space heating. Chinese household average electricity consumption in 2014 only amounted to 46.9% of the world average, 43.7% of the European Union, and 12.8% of the US (Le & Pitts, 2019). At present, electricity demand for space heating in Chinese households is tiny in comparison with developed economies having similar climate conditions (Bartels & Fiebig, 2000; Matsumoto, 2016; Newsham & Donnelly, 2013). Our findings show that the improvement of the educational level in China will increase residents' electricity demand, and that the growth potential is mainly in space heating. Regarding current patterns of usage, household electricity demand from entertainment and food refrigeration makes up around half of the total annual consumption. This requires a national policy on how to meet this demand with a clean energy supply. Besides, the increase of household income will increase electricity demand in the electrical services of laundry and hot water. Given that China is experiencing population aging, continuous improvement of residents' education level, and rising household income over the long term, the government should develop demand side management policies to address these substantial changes in socioeconomic variables and their significant impacts on electricity demand.

Second, energy providers and policy makers should recognize the urban-rural gap of energy demand and the heterogeneous impacts of socioeconomics factors. Our findings indicate that urban households spend a significantly higher proportion of electricity consumption than their rural counterparts for laundry, space cooling, and hot water. On the contrary, rural households consume a significantly higher share of electricity in terms of lighting. About 7.2% of total electricity is used for cooking by rural households, with urban counterparts hardly using electricity to cook. However, urban and rural residents share common usage habits in terms of space heating, and negligible electricity is used for this purpose. The revealed urban-rural service-specific electricity consumption gap

Table 6
Forecast of eight service-specific electricity consumption and expected net urban-rural ratio change.

	Age↑		Education↑		Income↑		Size↓		Teenager↓		Expected net urban-rural ratio change
	urban	rural	urban	rural	urban	rural	urban	rural	urban	rural	
Space cooling		↓					↓				uncertain
Laundry						↑					decrease
Hot water					↑					↓	increase
Space heating				↑							decrease
Entertainment						↓	↑				increase
Food refrigeration				↑							decrease
Lighting	↑				↓	↑	↓				uncertain
Cooking							↓				increase

Note: The symbols↑and↓denote the increase and the decrease of the corresponding socioeconomic variables or service-specific electricity consumption, respectively.

indirectly confirms the urban-rural carbon footprint inequality in China. Further, the heterogeneity in the impacts of socioeconomic variables on urban and rural residents' electrical demand is also an important consideration in policy-making. The improvement of the education level and the increase of household income will significantly increase the power demand of rural households for food refrigeration, laundry, and lighting services, while these developments will increase the power service demand of urban households for hot water. More importantly, the electrical service of space heating is bound to increase in both urban and rural areas. But the increase is driven in different ways: by the increase of household income in urban area (at 10% significance level) and by the improvement of residents' education level in rural area. This heterogeneity shows that it is important to tailor-make both policy objectives and implementation measures for differential electricity growth potentials in urban and rural areas in China.

Finally, this study suggests new applications for similar studies in other countries. We provide a model for appliance-service study and the socioeconomic determinants of electricity demand at the disaggregated level. We believe that the outcomes observed in other countries experiencing significant transitions in socioeconomic determinants can inform us of the patterns of appliance-service electricity demand. This will generate important policy implications to enhance the global environment. Of course, China and its history are unique in many ways, and extending the analysis to other countries or regions must be done carefully.

This study does not come without limitations. For one thing, due to data unavailability, only household survey data of China in 2014 is analyzed. Multi-year panel data is bound to reveal the dynamic and latest behavior of household electrical service demand. For another, the mechanisms of different socioeconomic variables driving different electrical service demand need to be further studied, in order to formulate more precise intervention policies.

Data availability

data are obtained from crecs.ruc.edu.cn.

Acknowledgement

Funding: This work is supported by the National Natural Science Foundation of China [Grant No. 72001065, 72261147760] and the Fundamental Research Funds for the Central Universities of China [Grant No. JZ2022HGTB0259].

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