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Impacts of family household dynamics on residential energy demands in Hebei Province of China

Yi Zeng[1,2*], Hanmo Yang[1], Zhenglian Wang[3,4] and Lan Li[5]

*Correspondence: zengyi@nsd.pku.edu.cn
[1] Center for Healthy Aging and Development Studies, National School of Development, Peking University, Beijing, China
Full list of author information is available at the end of the article

Abstract

This article presents analyses and projections of the residential energy demands in Hebei Province of China, using the ProFamy extended cohort-component method and user-friendly free software and conventional demographic data as input. The results indicate that the future increase in residential energy demands will be dominated by large increase in small households with 1–2 persons. We found that increase of residential energy demands will be mainly driven by the rapid increase of older adults' households. Comparisons between residential energy demand projections by household changes and by population changes demonstrate that projections by population changes seriously under-estimate the future residential energy demands. We recommend that China needs to adopt policies to encourage and facilitate older parents and adult children to live together or near-by, and support rural-to-urban family migration. Promoting inter-generation co-residence or living near-by between older parents and young adults would result in a mutually beneficial outcome for both older and younger generations as well as to effectively reduce energy demands. We suggest governments to carefully formulate strategies on efficient residential energy use to cope with the rapid households and population aging, and strengthen data collections/analyses on household residential energy demands for sound policy-making and sustainable development.

Keywords: Residential energy demands, Households and population aging, Family household projections, Older parents, Young adult children, Inter-generation co-residence

Introduction

Residential energy consumption is becoming a more and more important part of total energy consumptions in China and elsewhere. It accounts for 12.81 percent of total energy consumptions in 2018 in China, rising from 10.11 percent in 2010 (China Statistical Yearbook, 2020). Energy consumption of the residential sector in the US has increased from 17.52 percent in 1949 to 20.34 percent in 2018 (EIA, 2019). It seems likely that the proportion of residential energy consumption will continue to increase alongside urbanization, income growth, development of industries, shrinking of household size and increase in the number of households in China and elsewhere.

Hebei Province is in northeast China with a population of 75.92 million people in 2020 and median levels of socioeconomic development and urbanization. We focus on Hebei in present study due not only to its representativeness but also its geopolitical status, where it surrounds two of the four largest municipality cities (Beijing and Tianjin) in China. The coordinated development of Beijing–Tianjin–Hebei is one of the key development strategies of China. The rapid social and economic development in Hebei, Beijing, and Tianjin have created better opportunities for education and jobs, and stimulated population migrations within the province and outward to neighboring municipalities as well as other regions. According to the Seventh National Population Census in 2020, the migrant population in 2020 has increased by 129.71% as compared to 2010 in Hebei province (Hebei Provincial Bureau of Statistics, 2021). The majority of the migrants were younger adults which resulted in substantial increase of empty-nested older adults. A recent study on 4899 older adults aged 60+in Hebei Province showed that the proportion of the empty-nested older adults in rural areas was significantly higher than that in the urban areas, because many rural young people became migrant workers in the urban areas and left their old parents behind (Sun et al., 2020).

We believe that the study on future residential energy demands in Hebei province could provide important information for understanding the general trends and patterns of residential energy demands in China. From 2010 to 2019, the residential energy consumption in Hebei province has increased from 9.98 percent of total energy consumptions to 12.59 percent, and residential energy consumption per capita has risen from 363.52 kg of standard coal in 2010 to 539.78 kg of standard coal in 2019, increased by 48.49 percent, which significantly exceeds population growth rate during the same period—the total population in Hebei province only rose by 5.54 percent from 2010 to 2019. However, the number of households in Hebei grew by 27.61 percent, from 20.39 million in 2010 to around 26.02 million in 2019 (Hebei Statistical Yearbook, 2020).

Focusing on energy consumption in Hebei province, Liu and Zhu (2011) collected rural household survey data in Hebei province and investigated major factors that influence household energy consumption. Liu et al. (2011) estimated the relationship between energy consumption, CO_2 emission, and economic growth. Scholars investigated household energy consumption structure of Beijing Municipality, Tianjin Municipality and Hebei province and the influencing factors such as household structure and income (Zeng et al., 2018; Zhang et al., 2015). Gao and Yuan (2016) conducted a survey in all of the counties in Hebei on the habit and attitude for rural residents' energy consumption from the perspective of poverty alleviation, while their study was limited to rural areas only and they did not do any projections about future trends.

Growth in the number of households is a more important driving factor of residential energy consumption increase than population growth. There has been a rising consensus that households should be considered as the unit of analysis for energy consumptions, especially residential energy consumption (Liu et al., 2003; MacKellar et al., 1995). From 1970 to 1990, roughly three-quarters of energy consumption growth in developed countries is accounted for the growth in household numbers, while only one-third of the growth of energy consumptions can be explained by population growth (MacKellar et al., 1995). Energy-related consumption in the residential sector, such as cooking, space heating or cooling, and private vehicles, is undertaken by households, not individuals. Thus,

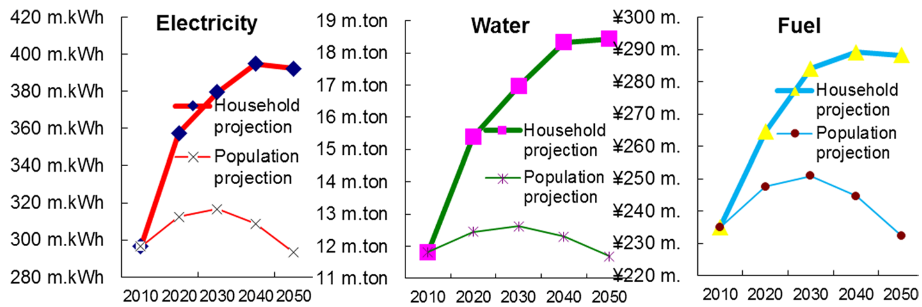

Fig. 1 Comparisons of the residential energy demand forecasting between projections based on household changes and population changes, Hebei province of China, 2010–2050. Notes: (1) "m." means millions; (2) the unit of electricity is "million kilowatt-hour (m.kWh)"; (3) the unit of water is "million ton" (m.ton); (4) the unit of fuel is "million yuan", i.e., the total currency costs of different fuels

residential energy consumption is driven by the growing number of households resulting from the smaller size of the residential units in the process of urbanization, population aging, and other compositional changes in the population (Dalton et al., 2008). The result of a survey on China's urban residents conducted in 2015 suggests a trend of larger energy usage per residential unit among the smaller family household (Hu et al., 2017).

Changing demographic factors (including higher divorce rates, more migrations, and the vanishing social norms that prescribe co-residence of old parents and adult children) contribute to smaller household size, and continuously and quickly increasing numbers of households all over the world (Gu et al., 2015). Consequently, it would seriously underestimate future years' energy consumption and mislead the policy makers, if the energy-use forecasting is based on population growth, which has slowed down greatly and will become negative soon in China and many other countries. In Hebei province, for example, the population growth rate decreased 38.5% in 2019 as compared to 2010 (Hebei Statistical Yearbook, 2020).

In Hebei, the average household size has decreased from 3.36 members in 2010 to 3.04 members in 2019 (Hebei Economic Yearbook, 2019; Hebei Statistical Yearbook, 2020). Figure 1 shows that the projection based on population changes seriously under-estimates the future residential energy demand in the Hebei province (see the first sub-section of the Results section of this paper for more detailed discussions). This is because population growth is very slow now and will become negative around 2035, but the number of households which truly determines home-based energy demands will continue to substantially increase in the next four decades in Hebei. Clearly, conducting household projections by types and sizes is crucially important in forecasting residential energy demands and strategic planning of environmental protections, and considering population changes only would seriously under-estimate future energy demands and mislead policy makers (Bradbury et al., 2014a, b; Keilman, 2003).

In this study, we investigate and conduct projections of the residential energy demands in Hebei province and focus on the effects of shrinking household size. Projecting residential energy demands is of great significance for coordinated development in Hebei Province, which is experiencing an economic transformation aiming at energy-saving and sustainable economic growth. Clearly, it is essential to project residential energy demands to provide a scientific and informative basis for energy policy design on coordinated development.

The method

In the present study, we use the ProFamy extended cohort-component method & free software for the projections of family households, living arrangement, and population age/sex distributions as well as residential energy demands in Hebei province. The ProFamy method presents an innovative and substantial extension of the classic approach of cohort-components projections of population only into simultaneous projections of households size/structure, living arrangements, population size, age and gender distributions, using the conventionally available demographic data; and the households projections can be readily used for home-based consumer goods and services demands forecasting, such as residential energy, housing, vehicles use, transportations, and elderly care needs/costs, etc. (Zeng Vaupel et al., 1998; Zeng et al., 2006, 2013a, b, c, 2014).[1] A summary note of the ProFamy extended cohort-component method (including illustration of the analytical passages) is presented in the Appendix of this article.

The ProFamy method and the user-friendly free software have been used to generate: implications of changes in U.S. households and living arrangements for the housing industry and policy-making (Smith et al., 2008, 2012); U.S. household and living arrangements projections by races and residential energy demands and future carbon emissions (Dalton et al., 2008; Jiang & O'Neill, 2007; O'Neill & Chen, 2002; O'Neill & Jiang, 2007); household automobile demands in Austria (Prskawetz et al., 2004) and the United States (Feng et al., 2011); fertility policy analyses, retirement ages and elderly care needs/costs studies in China (Feng et al., 2018; Zeng, 2007, 2011; Zeng et al., 2008); German household and living arrangement projections (Hullen, 2000, 2003); household and living arrangement projections in Brazil (Tirza, 2017), Mexico (Landy, 2017), and India (Feng et al., 2020a, b); estimating the fiscal impacts of changing household structures in Sri Lanka (Gruen, 2020); households and residential energy demands projections in Pakistan (Hussain & Sadiq, 2020).

The ProFamy model/software has also been used to produce household projections at sub-national and county/city levels for socioeconomic planning in the United States, Germany, Brazil, Iran, mainland and the Taiwan province of China (e.g., Bagi, 2018; Feng et al., 2020a, b; Hullen, 2003; Jiang & Kuijsten, 1999a, b; Smith et al., 2012; Tirza, 2017; Yang & Zeng, 2000; Zeng et al., 2013a, b, c). A notable example is that the local government office employed ProFamy method/software, the U.S. national race–age–sex-specific standard schedules and the demographic summary parameters at the county level to successfully project households and living arrangements for six counties in Southern California since 2009, with projections renewed every 2 years. The six counties' governments have effectively used these detailed biennial projections for their socio-economic planning, budget allocations, and policy analyses on housing, traffic, energy demands, elderly care, and other home-based social services (Feng et al., 2020a, b). Up to Nov.

[1] The ProFamy free software (with example of input database) and User's Guide can be found at www.profamy.com.cn.

2020, scholars from 27 countries, UNFPA and World Bank downloaded and used (or are using) ProFamy free software to do the research projects on household and living arrangement projections for informed decision-making.

Data source, the estimates and parameters of the projections

Data source and the estimates

Data needed for households and living arrangements projections at national and regional levels using the ProFamy method/software are listed in Table 5 of the Appendix, and we briefly summarize the data source and estimates for Hebei province here. Data on the baseline population of Hebei Province, classified by rural/urban residence, single year of age, sex, marital status, number of co-residing children and parents, and whether living in a private versus institutional household at the projection baseline year, were extracted from the micro-data file of the 2010 census of Hebei Province. The micro-data file provided by the Hebei Provincial Statistical Bureau consists of the de-identified individual census records for seven million persons, 10 percent of the total population in Hebei.

Based on the micro-data files of the 2010 census, we estimated rural/urban-single age–sex-specific mortality rates, rural/urban-single age–sex-specific occurrence/exposure (o/e) rates of first marriage and fertility by parity, age–sex-specific net migration frequencies between rural and urban areas within the province, and age–sex-specific external net migration frequencies. The model standard schedules of age–sex-specific o/e rates of divorce and remarriage were estimated using data from the four waves of China Family Panel Studies (CFPS) conducted in 2010, 2012, 2014, and 2016, with a total sample size of 48,804 interviewees aged 15–104. The rural/urban age–sex-specific probabilities of children leaving their parental homes were estimated based on 2000 and 2010 census data in Hebei and the iterated interpolating method within cohorts proposed by Coale (1985) and further extended by Stupp (1988).

Using the data sets of the annual household surveys in rural and urban areas conducted by the Hebei Provincial Statistical Bureau, we estimated the rural/urban-age–sex-household type/size-specific average residential energy consumptions of electricity, fuel and water per household. The estimates presented in Table 1 demonstrated a very interesting phenomenon, namely, the largest average residential energy consumptions per person is in the 1-person households, and the average residential energy consumptions per person decrease substantially with increase of the household size. For example, the average electricity consumptions pre person of the rural–urban combined households with 2 persons, 3 ~ 4 persons and 5 + persons were 13.2–24.4%, 33.8–53.2% and 47.5–70.6% lower than that of the rural–urban combined 1-person households; as compared with the 1-person households, the average fuel consumptions pre person of the 2 persons, 3 ~ 4 persons and 5 + persons were 20.1–36.1%, 37.8–64.9% and 58.9–69.6% lower (see Table 1).

The demographic parameters of the projections

To explore the impacts of family household dynamics on future residential energy demands in Hebei Province of China, we conduct projection of residential energy

Table 1 Average residential energy consumption per household and per person by rural/urban, household size and ages of householders, Hebei province, China, 2013

	1 person		2 persons		3 ~ 4 persons		5 + persons	
	Per household	Per person	Per household	Per person	Per household	Per person	Per household	Per person
Electricity (kilowatt hour)								
Rural and urban combined								
Aged 15–34	934.48	934.48	1412.06	706.03	1529.40	436.97	1595.45	275.08
Aged 35–64	763.43	763.43	1264.21	632.11	1510.50	431.57	1763.57	304.06
Aged 65 +	563.72	563.72	979.10	489.55	1305.75	373.07	1717.20	296.07
Rural								
Aged 15–34	701.36	701.36	1257.69	628.85	1372.97	392.28	1368.59	235.96
Aged 35–64	671.52	671.52	1062.37	531.19	1355.80	387.37	1668.38	287.65
Aged 65 +								
Urban								
Aged 15–34	1231.18	1231.18	1597.94	798.97	1750.48	500.14	2085.00	359.48
Aged 35–64	961.69	961.69	1667.89	833.94	1777.84	507.96	2009.60	346.48
Aged 65 +	797.90	797.90	1330.12	665.06	1619.70	462.77	1975.33	340.57
Water (ton)								
Rural and urban combined								
Aged 15–34	31.72	31.72	30.0	30.0	60.87	17.39	60.07	10.36
Aged 35–64	37.21	37.21	52.50	26.25	56.70	16.20	52.32	9.02
Aged 65 +	22.78	22.78	41.53	20.77	49.60	14.17	44.46	7.67
Rural								
Aged 15–34	10.07	10.07	19.0	9.5	34.2	9.8	48.56	8.37
Aged 35–64	26.57	26.57	37.43*	18.71	37.92	10.83	35.18	6.07
Aged 65 +	15.46	15.46	25.75	12.87	40.80	11.66	34.78	6.00
Urban								
Aged 15–34	59.27	59.27	93.53	46.77	90.04	25.73	84.89	14.64
Aged 35–64	60.16	60.16	82.64	41.32	89.16	25.47	96.61	16.66
Aged 65 +	40.43	40.43	72.38	36.19	66.39	18.97	72.29	12.46
Fuel (yuan)								
Rural and urban combined								
Aged 15–34	935.52	935.52	1495.52	747.76	1148.41	328.12	1324.32	228.33

Table 1 (continued)

	1 person		2 persons		3 ~ 4 persons		5 + persons	
	Per household	Per person	Per household	Per person	Per household	Per person	Per household	Per person
Aged 35–64	833.11	833.11	1064.15	532.07	1199.06	342.59	1466.81	252.90
Aged 65 +	592.82	592.82	906.26	453.13	1290.44	368.70	1413.00	243.62
Rural								
Aged 15–34	1405.50	1405.50	2059.97	1029.98	1289.89	368.54	1266.61	218.38
Aged 35–64	812.80	812.80	1063.09	531.55	1293.38	369.54	1439.03	248.11
Aged 65 +	522.60	522.60	871.00	435.50	1197.75	342.22	1451.01	250.17
Urban								
Aged 15–34	337.36	337.36	622.8	311.4	948.47	270.99	1448.84	249.80
Aged 35–64	876.90	876.90	1066.26	533.13	1036.06	296.02	1538.61	265.28
Aged 65 +	762.33	762.33	975.19	487.59	1467.13	419.18	1303.73	224.78

demands, which are associated with numbers, types, and sizes of households. The assumptions of the demographic parameters of the projections are outlined below.

Based on the data sets of the 2010 population census and the annual household surveys, we estimated that the rural–urban combined total fertility rate (TFR) in Hebei Province in 2010, adjusted for the under-reporting of births, was 1.76. This estimate is highly consistent with the estimates by the other scholars (e.g., Yin et al., 2013) and the Hebei Province governmental agency (Hebei Provincial People's Government, 2013). Considering that the strict family planning policy which allowed most couples to have only one child was relaxed to universal two-child policy in late 2015, the total fertility rate is estimated as 1.88 in 2017. Given the fact that China further relaxed fertility policy to returning fertility decision-making to family households since May 2021 and the quick socioeconomic development, we assume that the rural TFR and urban TFR remain unchanged at 2017 level, and the rural–urban combined TFR is expected to gradually decline to 1.8 in 2050 because of the large increase in proportion of the urban population which have much lower fertility level than that of the rural population (see Table 2).

Based on the mortality rates collected in the 1990, 2000, and 2010 censuses and the 1 percent population survey data collected in 1995 and 2005, stratified by urban and rural residence, age, and sex, we estimated the Hebei rural/urban and sex-specific average life expectancy at birth in 1990–2015 and extrapolated it to future years up to 2050 (see Table 2).

Following a simple trend extrapolation approach based on time series data of proportion of the urban population from the censuses and annual surveys of population changes, we projected that the proportion of urban residents among the total population in Hebei will be 63 and 75 percent in the years 2030 and 2050, respectively (see Table 2). Based on the trend extrapolation method and data from censuses conducted in 1990,

Table 2 Main demographic parameters 2010–2050, Hebei Province, China

	Rural			Urban			Rural–urban comb		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Total fertility rate	2.0	2.1	2.1	1.3	1.7	1.7	1.7	1.8	1.8
Male life expectancy at birth	70.9	74.3	77.4	74.2	75.7	79.3	72.4	75.2	78.8
Female life expectancy at birth	74.7	78.3	81.3	78.3	82.3	85.0	76.3	80.8	84.1
Male general rate of in-migration	0.0025	0.0040	0.0069	0.0018	0.0016	0.0026	0.0022	0.0025	0.0037
Female general rate of in-migration	0.0027	0.0042	0.0069	0.0019	0.0017	0.0027	0.0023	0.0026	0.0038
Male general rate of out-migration	0.0023	0.0037	0.0062	0.0017	0.0014	0.0024	0.0020	0.0023	0.0033
Female general rate of out-migration	0.0017	0.0028	0.0046	0.0012	0.0011	0.0018	0.0015	0.0017	0.0025
Proportion of urban population				0.44	0.63	0.75			
Mean age at first marriage, male	25.3	24.6	24.6	26.3	26.3	26.3	25.7	25.7	25.9
Mean age at first marriage, female	23.1	22.7	22.7	24.9	24.9	24.8	23.9	24.1	24.3
Mean age at births	25.2	26.5	26.5	26.6	27.8	27.8	25.8	27.3	27.4
General rate of marriages	0.1146	0.1146	0.1146	0.0908	0.0908	0.0908	0.1041	0.0996	0.0968
General rate of divorce	0.0039	0.0039	0.0039	0.0095	0.0095	0.0095	0.0064	0.0074	0.0081

2000, and 2010, we estimated the sex-specific general rate of in-migration from other provinces and the sex-specific general rate of out-migration to other provinces (Table 2).

We estimated the sex-rural/urban-specific general marriage rate and divorce rate based on the 2010 census data and the total number of marriages and divorces in 2010 published by the Bureau of Civil Affairs of Hebei Province, and we assumed that the sex-rural/urban-specific general marriage rate and divorce rate remain unchanged in the medium scenario (Table 2). All demographic parameters and per-household average energy demand rates for all individual years between 2010, 2035, and 2050 are linearly interpolated.

The rural/urban-age–sex-household type/size-specific average residential energy consumptions of electricity, fuel and water per household are multiplied by the corresponding rural/urban-age–sex-household type/size-specific numbers of households projected by the ProFamy extended cohort-component approach to yield projected residential energy demands in future years. The average residential energy consumptions of electricity, fuel and water per household classified by age, sex, household type, and size were assumed to remain unchanged in future years.

Note that we employ the common approach of holding the rural/urban-age–sex-household type/size-specific average residential energy consumption rates per household unchanged throughout the projection horizon, which is the best available choice, given that scientific theories and past history do not provide a reliable basis for accurately predicting how those rates will change (e.g., Day, 1992; Smith et al., 2001; Treadway, 1997). In addition, holding the residential energy consumptions per household of different types and sizes unchanged allows us to focus on exploring how dynamics of family households induced by possible future changes in demographic rates of marriage formation and dissolution and co-residence between old parents and adult children may affect future residential energy demands.

Note that this paper aims to provide a general profile of projections of the future trends of impacts of family household dynamics on residential energy demands, in the context of rapid population aging. A sensitivity analysis on the impacts of high or low scenarios of fertility, mortality, marriage, and divorce as well as average residential energy consumptions per household by household types/sizes and ages of the householders would create huge complexities and it is out of the scope of this paper. Thus, we will focus on the medium projections as outlined above.

The assumptions about fertility, mortality, migrations, general rates of marriage, divorce, co-residence between old parents and adult children in 2030 and 2050 constitute our educated guesses about the possible changes in demographic parameters in the next few decades. Although we made these guesses with reference to the available time-series data, they are still to some extent arbitrary because of uncertainties about future trends. Nevertheless, similar to conventional population projections, our projections presented in this paper formulate possible future residential energy demands due to possible family household dynamics.

Results of the projections

Comparisons between the projections of residential energy demands by household changes and by population changes, 2010–2050

To illustrate the importance of including the household types and sizes in residential energy demands projections, we conducted and compared the projection results by household changes and by population changes. The results of projection by household changes are derived by multiplying the average energy demands per household unit by projected numbers of households of different types and sizes, and the results of projections by population changes are derived by multiplying the average energy demands per person by total population size. Figure 1 shows that the residential energy demands projections by population changes seriously under-estimate the future residential energy demands in Hebei. This is because the growth of population size is very slow now and will become negative around 2035, but the number of households, which truly reflect the actual residential energy demands, will continue to increase in the next four decades. Clearly, inclusions of household numbers by types and sizes are crucially important in forecasting residential energy demands, and considering population changes only would seriously under-estimate residential energy demands and have serious negative effects on decision-making and sustainable development plans.

The residential energy demands by household sizes, 2010–2050

Figure 2 indicates that the the highest relative increase of residential energy demands in 2050 as compared to 2010 is water, the next is electricity and the third is fuel. Figure 3 indicates that the highest relative increase of residential energy demands of electricity, fuel and water is by 1-person-only households, increased by about 240, 230 and 300 percent, respectively, in 2050 as compared to 2010; and the second-highest increase is by 2-person households. Table 3 shows more detailed numerical results of the relative increase of residential energy demands in 2050 as compared with 2010, by household size, age groups of the householder, and rural/urban residence in Hebei province. As indicated in Table 3, the relative increase of residential energy demands of electricity,

Table 3 Relative % increase of residential energy demands in 2050 as compared with 2010 by rural/urban, household size and ages of householder, Hebei province, China

	1 person	2 persons	3~4 persons	5+persons	Total
Electricity					
Rural and urban combined					
Aged 15–34	111.26	60.54	− 27.57	− 49.02	− 23.53
Aged 35–64	259.96	86.08	− 5.76	− 44.20	11.53
Aged 65+	343.69	491.23	4878.92	1269.34	647.86
Total	242.10	156.34	7.17	− 44.33	31.63
Rural					
Aged 15–34	19.62	− 23.96	− 75.66	− 76.76	− 72.47
Aged 35–64	− 24.23	− 60.05	− 70.61	− 70.08	− 67.62
Aged 65+	85.77	228.75	3533.90	1102.56	345.78
Total	20.75	− 2.05	− 58.35	− 71.23	− 51.02
Urban					
Aged 15–34	132.99	89.43	15.41	− 17.02	19.71
Aged 35–64	462.68	192.72	55.13	− 3.39	89.67
Aged 65+	588.28	695.17	6105.71	1436.54	897.91
Total	374.42	265.35	67.90	− 7.30	110.16
Water					
Rural and urban combined					
Aged 15–34	125.50	67.70	− 15.31	− 46.97	− 12.67
Aged 35–64	311.28	106.37	11.92	− 30.66	36.90
Aged 65+	395.94	548.27	4966.22	1313.21	681.68
Total	286.90	180.96	22.90	− 36.69	56.11
Rural					
Aged 15–34	19.62	− 23.96	− 75.66	− 76.76	− 73.04
Aged 35–64	− 24.23	− 60.05	− 70.61	− 70.08	− 66.68
Aged 65+	85.77	228.75	3533.90	1102.56	357.39
Total	16.49	− 6.12	− 54.85	− 72.39	− 47.98
Urban					
Aged 15–34	132.99	89.43	15.41	− 17.02	22.86
Aged 35–64	462.68	192.72	55.13	− 3.39	93.34
Aged 65+	588.28	695.17	6105.71	1436.54	847.19
Total	386.47	268.36	63.37	− 7.19	113.86
Fuel					
Rural and urban combined					
Aged 15–34	61.09	30.11	− 39.94	− 53.21	− 36.84
Aged 35–64	225.87	57.94	− 21.04	− 46.06	− 1.75
Aged 65+	323.77	445.23	4784.18	1244.42	610.97
Total	226.18	131.61	− 2.23	− 47.31	22.72
Rural					
Aged 15–34	19.62	− 23.96	− 75.66	− 76.76	− 69.29
Aged 35–64	− 24.23	− 60.05	− 70.61	− 70.08	− 67.19
Aged 65+	85.77	228.75	3533.90	1102.56	337.22
Total	19.04	0.85	− 56.92	− 71.34	− 47.82
Urban					
Aged 15–34	132.99	89.43	15.41	− 17.02	12.27
Aged 35–64	462.68	192.72	55.13	− 3.39	94.32
Aged 65+	588.28	695.17	6105.71	1436.54	922.47
Total	455.31	280.67	81.85	− 7.22	125.62

fuel and water of one-person only households in 2050 will be 242.10, 226.18 and 286.90 percent, respectively. In contrast, the relative increase of residential energy demands of electricity, fuel and water of all households with different sizes combined in 2050 will be 31.63, 22.72 and 56.11 percent, respectively. This is because of the large increase in the number of 1-person and 2-person households. However, the energy demands by 3–4 person households will be almost the same and the energy demands by the 5 + person households will decrease by 36 ~ 58 percent in 2050 compared with that in 2010 (Fig. 2 and Table 3). The results show that the residential energy demands increase in the next few decades will be dominated by a large increase of the small households with one or two persons. This trend consequently leads to higher residential energy demands per capita, because smaller household size means fewer people sharing their house, appliances, and vehicles and a decrease in the efficiency of energy use.

The residential energy demands by age groups of householders, 2010–2050

Table 4 presents the results of projected amount of the residential energy demands by types of energy, rural/urban and ages of householders in Hebei province from 2010 to 2050. We found that in 2010, the electricity consumed by households of older adults aged 65 + was 17.13 mkWh, and it will reach 111.15 m kWh in 2050, which is 6.48 times as large as that of residential energy consumption in 2010 (see Table 4. Figure 4 also shows that the huge relative increase in energy demands in 2050 compared to 2010 is revealed among the older adults' households. The residential energy demands of electricity, fuel and water by households of older adults aged 65 + will also increase much faster than those by the younger age groups. The largest relative increase of three types of residential energy demands is found for rural–urban combined older adults households with 3–4 persons, all nearly 50 times higher in 2050 as compared with 2010 (Table 3).

These results are consistent with previous studies (Tonn & Eisenberg, 2007; Yamasaki & Tominaga, 1997). The imminent rapid population aging in China will result in a much larger proportion of the elder population and households with older adults, who have a very different lifestyle as compared to the youth. They have much less active life, reduced demands for energy demands of household appliances and vehicles. However, the elderly spend much more time staying at home and need more stable room temperature, which will result in higher residential energy demands. Our results show residential energy demands will be mainly driven by elder people because of the large increase in the number of elder households. Energy demands of households under 35 years will substantially decline in the years 2010–2050. Overall, it's important to consider the households and population aging trends and analyze their influences on residential energy demands.

The residential energy demands by rural/urban residence, 2010–2050

Figure 5 shows that the residential energy demands in urban areas of Hebei Province will increase by 110.20–125.60 percent in 2050 compared to 2010, but the total demand of energy demands in the rural area will decrease substantially, and Table 3 also shows the same trends. This is because of urbanization. Not only due to that urbanization results in rural residents migrating to cities, but also because it changes the household structure, people's lifestyles and the household energy consumption pattern are more substantial in urban areas than in rural areas. For instance, urbanization has led to more

Table 4 Residential energy demands by types of energy, rural/urban and ages of householders, Hebei province, China, 2010–2050

	2010	2015	2020	2025	2030	2040	2050
Electricity (million kWh)							
Rural and urban combined							
Aged 15–34	82.74	98.87	93.43	64.98	51.88	63.70	62.62
Aged 35–64	194.35	214.67	239.06	270.44	271.14	239.41	231.76
Aged 65+	17.13	19.49	27.28	41.52	63.55	97.24	111.15
Total	294.22	333.03	359.77	376.94	386.56	400.35	405.53
Rural							
Aged 15–34	37.70	35.87	23.80	10.74	7.23	5.15	1.71
Aged 35–64	96.54	92.38	94.17	86.60	67.97	35.02	18.17
Aged 65+	7.83	7.53	10.99	20.45	27.40	29.44	23.81
Total	142.07	135.77	128.95	117.79	102.60	69.61	43.68
Urban							
Aged 15–34	45.03	63.01	69.64	54.24	44.64	58.55	60.92
Aged 35–64	97.81	122.29	144.89	183.84	203.17	204.39	213.59
Aged 65+	9.30	11.95	16.29	21.07	36.15	67.80	87.34
Total	152.15	197.25	230.82	259.15	283.97	330.74	361.85
Water (million ton)							
Rural and urban combined							
Aged 15–34	3.44	4.30	4.21	3.03	2.47	3.09	3.07
Aged 35–64	7.61	8.78	9.99	11.72	12.17	11.30	11.24
Aged 65+	0.75	0.88	1.22	1.79	2.75	4.36	5.13
Total	11.80	13.95	15.43	16.55	17.39	18.74	19.44
Rural							
Aged 15–34	1.26	1.21	0.81	0.38	0.26	0.18	0.06
Aged 35–64	2.69	2.63	2.71	2.49	1.98	1.04	0.54
Aged 65+	0.25	0.25	0.36	0.68	0.92	0.99	0.80
Total	4.21	4.08	3.88	3.56	3.16	2.21	1.40
Urban							
Aged 15–34	2.18	3.08	3.40	2.66	2.21	2.91	3.01
Aged 35–64	4.92	6.15	7.28	9.23	10.19	10.25	10.70
Aged 65+	0.50	0.63	0.86	1.11	1.83	3.37	4.33
Total	7.59	9.86	11.55	12.99	14.23	16.53	18.04
Fuel (million yuan)							
Rural and urban combined							
Aged 15–34	65.02	75.33	66.98	44.94	35.34	38.33	34.86
Aged 35–64	154.17	165.21	181.80	200.64	196.08	164.87	155.22
Aged 65+	15.56	17.50	24.69	38.54	58.47	86.69	96.60
Total	234.75	258.04	273.47	284.12	289.89	289.89	286.68
Rural							
Aged 15–34	39.53	40.27	28.19	15.10	11.50	7.51	2.40
Aged 35–64	91.72	88.15	90.14	82.95	65.37	33.90	17.59
Aged 65+	8.51	8.22	11.90	21.95	29.38	31.66	25.62
Total	139.76	136.64	130.24	120.00	106.25	73.07	45.61
Urban							
Aged 15–34	25.49	35.06	38.79	29.84	23.84	30.82	32.45
Aged 35–64	62.45	77.06	91.66	117.69	130.71	130.97	137.64
Aged 65+	7.05	9.28	12.78	16.60	29.09	55.03	70.98
Total	94.99	121.40	143.23	164.12	183.64	216.82	241.07

kWh kilowatt hour

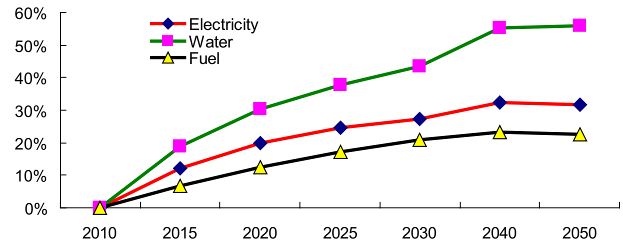

Fig. 2 Relative increases of residential energy demands of electricity, water and fuel in different future years, as compared to 2010

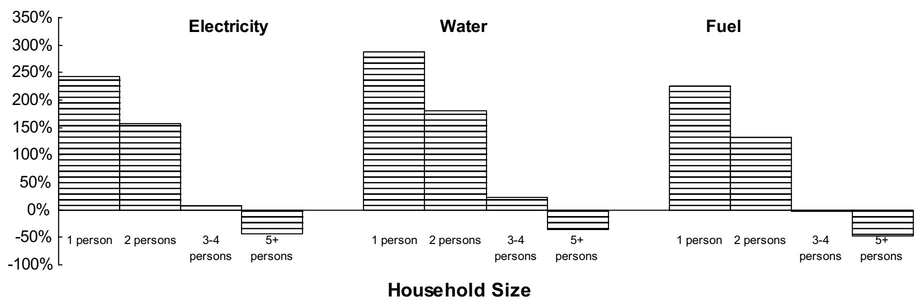

Fig. 3 Relative increase of residential energy demands of electricity, water and fuel by household size in 2050 as compared to 2010, Hebei, China

household electricity facilities and other appliances, resulting in higher residential electricity demands (Wang et al., 2016).

Discussions, policy recommendations, and conclusions

Applying the ProFamy extended cohort-component method and user-friendly software, this article presents analyses and projections of the residential energy demands in Hebei Province of China and focuses on the effects of shrinking household size and population aging. We projected future residential energy demands from 2010 to 2050. As shown in Fig. 1, which compares the residential energy demand projections by household changes and by population changes, it is clear that projections by population changes seriously under-estimate the future residential energy demands. The results presented in this article indicate that the future increase in residential energy demands will be dominated by the large increase in the small households with one or two persons. Due to quick urbanization, the total energy demands in urban areas will increase substantially, but in contrast, the total energy demands in rural areas will substantially decline. We found that the increase of residential energy demands will be mainly driven by the rapid increase of older adults' households.

Considering the serious challenges of households and population aging, we propose three policy recommendations for improving efficiency of residential energy demands in the context of rapid socio-economic changes in China. First, China needs to adopt policies to encourage and facilitate older parents and adult children to live together or near-by, and support rural-to-urban family migrations or family

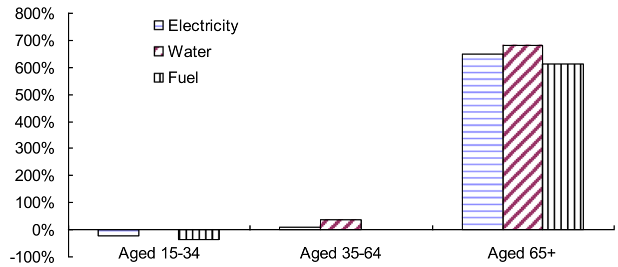

Fig. 4 Relative increase of residential energy demands in 2050 as compared to 2010 by ages of householder

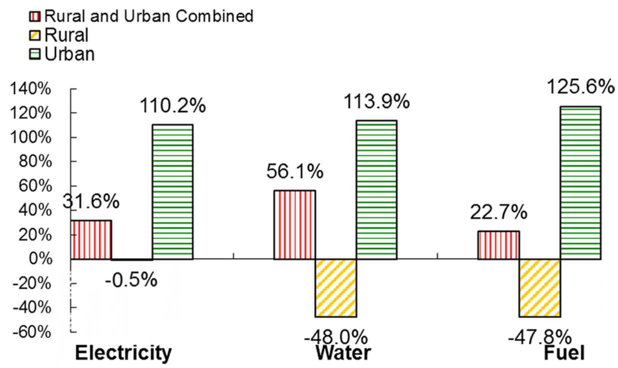

Fig. 5 Relative increase of residential energy demands in 2050 as compared to 2010, classified by rural and urban areas

reunions after young migrants are settled in urban areas. Singapore government has been successfully implementing the policy of subsiding three-generation households and living close-by of old parents and their adult child(ren). For example, Singapore government provides 30,000 and 20,000 Singapore dollars of housing subsidy to those three-generation households and those old parents and adult child(ren) who live near-by, respectively, to promote inter-generational assistances of respecting old and caring for young (Yang, 2014). China may get enlightenment from the successful experiences of Singapore in offering financial subsidy for inter-generation co-residence or living near-by between older parents and young adults (Liang, 2014). It would result in a mutually beneficial outcome for both older and younger generations, as well as the effective reduction of energy demands (Fig. 5).

Second, we suggest carefully formulate strategies on residential energy demands plans to cope with the challenges of households and population changes in the next decades. The policies should emphasize increasing energy utility efficiency, including green building of aged-friendly housing, household energy-saving devices, green energy devices, etc. A key point is to promote the transformation of residential energy consumption patterns from traditional to more efficient and energy-saving lifestyle (Hu et al., 2017).

Third, the current data availability of residential energy demands at regional and county/city levels are insufficient and cannot meet the needs for sound decision-making and socioeconomic planning. Thus, we propose that the governmental agencies and society to strengthen the data collections and analyses on household residential energy demands for informed policy-making and sustainable development.

In conclusion, understanding the on-going and future trends of households and living arrangements dynamics is essential to analyses and projections of residential energy demands in Hebei and elsewhere, and it is one of the crucial steps towards a sustainable development future.

Appendix: A summary note on ProFamy extended cohort-component method and input data for households and living arrangement projections

In this summary note, we first briefly summarize the methodology, input data needed, and assessments of applications of the ProFamy extended cohort-component method/software for household and living arrangement projections. We also introduce applications of the user-friendly modules DemoRates and BasePop of the ProFamy software package to contact empirical data analyses (rather than projections only) using the census and demographic survey data sets.

A brief introduction of the ProFamy method

Benefiting from methodological advances in multistate demography (Land & Rogers, 1982; Willekens et al., 1982), Bongaarts (1987) innovatively developed a nuclear-family-status life table model. Zeng (1986, 1991) extended Bongaarts's nuclear-family-status life table model into a general-family-status life table model that includes both nuclear and three-generation family households. Based on Bongaarts's and Zeng's one-sex life table models, Zeng et al. (1998) initially proposed and Zeng et al. (2006, 2013a, b, c) further developed the ProFamy model, which is a two-sex multistate cohort-component method that projects numbers of individuals by sex, age and statuses of marriage/union, numbers of co-residing children and parents, and derives household types/sizes from these projected individuals' statuses. The ProFamy extended cohort-component method/software projects simultaneously the households of various types and sizes (ref. Table 2 in Zeng et al., 2006), and sex, age and living arrangements distributions of all individual members of the population under study. The projection outcome of the population age/sex distributions produced by ProFamy approach are fully consistent with those produced using the standard cohort-component population projection approach, as long as both approaches use the same input data of fertility, mortality and migration. Clearly, the ProFamy method overcomes the serious shortages of the classic headship-rate method, that is not linked to demographic rates, projects only a few household types without size information, and deals with household "heads" but not other household members.

The ProFamy model applies the harmonic mean to ensure consistencies between the two sexes and between children and parents. More specifically, the numbers of new marriages and cohabiting union formations each year among males are ensured to equal those among females, and numbers of children who leave (or return to) the parental homes each year are ensured to be equal to the corresponding numbers of

Table 5 Data needs to project households and living arrangements using the ProFamy extended cohort-component method, with a comparison to standard population projections

Contents of the needed data for the projections	ProFamy household projection	Pop Projection
(1) Baseline population of starting year of projection at national or sub-national level		
(a) A census micro sample or population register or an exceptionally large survey data file with only a few needed demographic variables, including sex, age, marital/union status, relationship to the householder, and whether living in a private or institutional household; (b) Published 100% census tabulations of age–sex-specific (and marital status-specific if possible) distributions of the entire population, and aggregated numbers of households	√ (and a few more available variables from census micro data)	√
(2) Age–sex-specific standard schedules at the national level (can be used for projections at sub-national and county/city levels), estimated by ProFamy R software DemoRates using commonly available data of demographic surveys or census micro file	Estimated by ProFamy R software DemoRates or or standard statistical software.	
(a) Age–sex-(and marital-status if possible)-specific mortality rates;	√	√
(b) Age–sex-specific rates of international immigration and emigration, or age–sex-specific rates of international net-migration;	√	√
(c) Age–sex-specific rates of domestic in-migration and out-migration if the projections are for the sub-national regions;	√	√
(d) Age-specific fertility rates; (e) Age-parity-specific o/e rates of marital and non-marital fertility; (f) Age–sex-specific o/e rates of marriage/union formation and dissolution;	√ √ √	√
(g) Age–sex-specific net rates of leaving the parental home, estimated based on two adjacent census micro data files and the intra-cohort iterative method (Coale, 1984, 1985; Stupp, 1988; Zeng et al., 1994), using the ProFamy software	√	
(3) Demographic summary parameters for the nation or sub-national regions or counties in the baseline and selected future projection years		
(a) Total Fertility Rates (TFR) by parity; (b) Sex-specific life expectancies at birth; (c) Sex-specific general rates of in-migration and sex-specific general rates of out-migration; (d) Sex-specific mean ages at first marriage and mean age at births;	√ √ √ √	√ √ √
The summary measures (e) ~ (j) listed below for the baseline year are automatically estimated by ProFamy software using the census (or population register) micro data file (see Sect. (1)), users will decide whether they keep constant or change in future years: (e) Total rates of marriages and divorces; (f) Total rates of cohabitation union formation and dissolution, if cohabitation status is included and the data are available; (g) Proportion of those aged 45–49 who do not live with parents; (h) Age–sex-specific proportion of persons living in group quarters (collective households)	√ estimated by ProFamy R software DemoRates or standard statistical software, using the data of census, demographic surveys or population register	

parents who experience the changes in the number of co-residing children (Zeng et al., 1998).

Input data needed to run ProFamy model for household and living arrangement projections

As commented by Willekens (2010:11), a major strength of ProFamy model is that the family and household dynamics are derived from demographic events, and consequently, it requires conventional demographic data that are available from ordinary surveys, population registers, vital statistics and censuses (see Table 5). Because its reliance on demographic rates, ProFamy provides a tool to quantitatively assess the effects of demographic changes in marriages/unions, divorces, fertility, mortality, migrations, etc., on household and living arrangement dynamics (Willekens, 2010).

Note that the needed age–sex-specific net rates of leaving the parental home and the summary measures (e)–(j) listed in Sect. (3) of Table 5 will be estimated by the ProFamy software using the commonly available census micro file (or population register data) (see (a) of Sect. (1) in Table 5). In fact, as demonstrated in Table 5, in addition to the basic data for standard population projections, the major work of data preparation for household and living arrangement projections using the ProFamy extended cohort-component method/software is to estimate the age-parity-specific o/e rates of marital and non-marital fertility and the age–sex-specific o/e rates of marriage/union formation and dissolution, which will be discussed in more details later in this note.

As Keyfitz (1972) pointed out, demographic projections based on trend extrapolation of each age–sex-specific rate could result in an excessive concession to flexibility and readily produce erratic results. Accordingly, analysts should use the fixed age–sex-specific standard schedules (Sect. (2) of Table 5) and concentrate on projecting future changing demographic summary parameters (Sect. (2) of Table 5) in population, household and living arrangement projections. Numerous studies have demonstrated that the fixed age–sex-specific standard schedules and a few changing summary parameters offer an efficient and realistic approach for demographic projections (Brass, 1974; Coale et al., 1983). The theoretical foundation of this practice is that the changing demographic summary parameters are crucial to determine dynamics in level and age pattern of the age-specific rates which affect the projections. At the same time, the projection results typically are not highly sensitive to the fixed age–sex-specific standard schedules. Thus, the national age–sex-specific standard schedules can be readily employed for household and living arrangement projections at the sub-national and county/city levels using the ProFamy method/software, as empirically tested in various studies (Smith et al., 2012; Zeng et al., 2013a, b, c, 2014), or even be used for projections or estimations in other countries with similar demographic patterns, as corroborated in Zeng et al. (2000).

The data categories of race or rural/urban regions are optional based on the actual demographic situation and data availability of the country or regions or county/city under study. If the categories of race or rural/urban regions are adopted in the application, all data listed in this table will need to be race-specific or rural/urban-region-specific.

Assessments of the ProFamy extended cohort-component method

Assessments validated the accuracy of projections using the ProFamy model for the United States and China from 1990 to 2000, namely, the forecast errors, measured by discrepancies between the projected values and the 2000 census observations, are reasonably small (Zeng et al., 2006, 2008). The test comparisons of the ProFamy projections from 1990 to 2000 with census counts in 2000 for each of the 50 U.S. states and DC showed that 63.0, 17.4, 12.9, and 6.7 percent of the absolute percentage errors were < 3.0%, 3.0–4.99%, 5.0–9.99% and ≧10.0%, respectively, among 306 pairs of comparisons of the main indices of household projections between forecasts and the census observations (Zeng et al., 2013a, b, c). Similar assessments for each of the 31 Chinese provinces show that the ProFamy method/software works well. Tests of projections of households and living arrangements in 2000–2010 and comparing the results with the 2010 census counts for the six counties of Southern California validated the applications of ProFamy approach at county/city level (Feng et al., 2020a, b). Another assessment compares average forecast errors between the ProFamy approach and the classic headship-rate method, by projecting the number-of-bedrooms-specific housing demands from 1990 to 2000 and then comparing them with census counts in 2000 for each of the U.S. 50 states and DC. The results demonstrate that, as compared to the ProFamy approach, the headship-rate method produces much more serious forecast errors, because it projects household types only but not by sizes (Zeng et al., 2013a, b, c).

Using ProFamy user-friendly software module BasePop for empirical analyses on household dynamics based on census data

BasePop module of ProFamy free software could also be used to utilize censuses' micro censuses data sets available to the users (or publically available at IPUMS database of university of Minnesota) and the officially published census 100% summary cross-tabulations to produce not only proportions as usual but also 100% absolute numbers of households by types and sizes and elderly, adults and children by various living arrangements, to which standard statistical software could not usually produce.

Governmental socioeconomic planning and private business market analyses need not only detailed proportion distributions but also absolute numbers of households by types and sizes living arrangements of elderly, children and adults. In some circumstances, the information of dynamic changes in absolute numbers are more useful than that of proportions in socioeconomic planning and market analyses. For example, the absolute numbers of Chinese oldest-old age 80 and older living alone (who may likely need care services) increased by 233.2 percent from 1990 to 2010. In contrast, the increase in the proportion of oldest-old living alone among total population was 21.8 percent in the same period.

The statistical offices publish cross tabulations of both proportions and absolute numbers based on the 100 percent census data, but these cross tabulations only contain certain rather limited broad categories and do not have detailed information of households by types/sizes and do not contain much information about living arrangements of elderly, children and adults. Thus, scholars rely on the data source of census micro samples to estimate the proportion distributions by detailed types of households and living arrangements, which are useful for academic research and policy analysis.

However, almost all the previously published studies on households and living arrangements based on the census micro data include only proportion distributions without detailed information about the cross-sectional and dynamic changes in absolute numbers. This is because that it is not valid to simply multiply the detailed proportion distributions of households and living arrangements derived from the census micro sample data by the absolute numbers of the limited summary measures officially published based on the 100 percent census data to estimate the corresponding detailed absolute numbers, as it would produce results that are not internally and logically consistent.

Thus, to avoid the inconsistency, one could apply the user-friendly BasePop module of the ProFamy model and software to estimate both proportions and detailed absolute numbers of 100 percent population distributions of households by types/sizes and living arrangements of elderly, children and adults by age, sex and rural–urban residence (or race) in the census year, while ensuring internal consistencies and accuracy. Such application of the BasePop module of the ProFamy software not only produces a baseline for the households and living arrangement projections, but also facilitates the analyses for those who may not be interested in projections but interested in households and living arrangements dynamics in the past years by analyzing 2 or 3 or more censuses micro data available to them (or publically available at IPUMS database of University of Minnesota).

Using ProFamy user-friendly software module DemoRates to estimate the age–sex-specific standard schedules of the demographic rates

As demonstrated in Table 5, in addition to the same basic input data as the standard population projections require, the additionally needed age–sex-specific net rates of leaving the parental home and the summary measures (e)–(j) listed in Sect. (3) of Table 5 are estimated by the ProFamy software using the census micro data. Thus, the main task of data preparation to use ProFamy extended cohort-component method/software for household and living arrangement projections is to estimate the age–sex-specific standard schedules of the occurrence/exposure (o/e) rates of marriage/union formation and dissolutions and the age-parity-specific o/e rates of marital and non-marital fertility. Note that lack of these o/e rates of age–sex-specific standard schedules in many countries is the main barrier of broader applications of ProFamy method for detailed and useful projections of households and living arrangements. However, these needed o/e rates of age–sex-specific standard schedules can in fact be relatively easily estimated, using the fertility and marriage histories data collected in the ordinary fertility/family surveys in most countries and/or in population registers if available (Zeng et al., 2012: 214–215).

Estimations of these age–sex-specific o/e rates can be relatively easily done by employing ProFamy user-friendly & free R software DemoRates (www.profamy.com.cn). Using the age–sex-specific standard schedules at the national level estimated by the researchers themselves or someone else and projected or assumed summary parameters in the future years, researchers and statistical offices can conveniently perform the forecasts of households and living arrangements at national, sub-national and county/city levels through employing the user-friendly & free ProFamy software (www.profamy.com.cn).

Abbreviations
TFR: Total fertility rate; o/e rates: Occurrence/exposure rates; CFPS: China Family Panel Studies; m: Millions; kWh: Kilowatt hour; m.kWh: Million kilowatt hour; m.ton: Million ton.

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Authors' contributions
ZY supervised this work; LL contributed to apply and obtain the data sets for the research of this article; WZL and YHM did the numerical data analyses and projections. All authors discussed and contributed to the theoretical framework, interpretations of the results. All authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from Statistical Bureau of Hebei Province in China, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission of Statistical Bureau of Hebei Province in China.

Declarations

Competing interests
The authors declare that we do not have any financial and non-financial conflicts of competing interests of the works reported in this article.

Author details
[1]Center for Healthy Aging and Development Studies, National School of Development, Peking University, Beijing, China. [2]Center for the Study of Aging and Human Development and Geriatrics Division, Duke University, Durham, USA. [3]China Population and Development Research Center, Beijing, China. [4]Center for Population Aging and Health, Population Research Institute, Duke University, Durham, USA. [5]Institute of Macroeconomic Research, Commission of Development and Reform, Shijiazhuang, Hebei, China.

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