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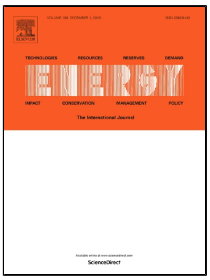

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Abstract: Rural energy consumption not only significantly affects the national economy but also affects the living conditions of rural residents. A comprehensive survey of households in the agropastoral area of Qinghai Province was conducted from 2017-2018 to identify its energy consumption characteristics. In this paper, a typical household energy flow model was established. The results show that 1) the proportion of noncommercial energy in the agropastoral area of Qinghai Province is 52.89%, and it is affected by the 'returning farmland to forest' (RFF) policy and the 'returning grazing land to grassland project' (RGLGP). Furthermore, the household energy consumption structure has shifted from traditional biomass to coal and a combination of other energy sources. 2) Households of different cultural backgrounds have different energy consumption patterns. 3) High-income households consume more energy and have more frequent energy flows compared with low-income households. The results of this survey will help policymakers and scholars to formulate strategies for energy conservation and more effectively assess energy policies.

Keywords: household energy consumption; energy geography; material flow model; Qinghai-Tibet Plateau; agropastoral areas

1. Introduction

Energy sustainability is one of the core topics for addressing sustainable development goals for 2030, and it is also critical for tackling climate change (UN, 2015; UNFCCC, 2015). With accelerating industrialization and urbanization, household energy consumption has become a major source of growth in global energy demand in developing countries (Kammen et al., 2016). In China, household energy consumption has been growing faster than industrial energy consumption since 2011 (Mi et al., 2018). In 2016, the Chinese government issued the

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‘energy production and consumption revolutionary strategy’, in which the incremental energy of the service and residential sectors will account for 60% of total final energy demand from 2015 to 2035 (NDRC, 2016). Considering that 80% of consumer behavior in societal consumption is controlled and implemented by the household sector, the household-based unit is more fundamental than the individual consumer and can provide comprehensive information on household energy consumption, thus helping to distinguish between challenges and opportunities and providing guidance for later policy measures（Dianshu et al., 2010).

Agropastoral areas are regional ecosystem transition areas in agricultural and pastoral areas. Because it is a zonal area featuring a combination of nomadic culture and arable land culture, the land use form is a combination planting and animal husbandry and plantations and settlements are located on arid grasslands. Over time, planting and grazing have shown rising and falling trends, respectively, driven by the seasons and government policies. Presently, the ecological environmental quality of China's agricultural and pastoral areas has gradually declined, which has had a serious lag effect on local economic development. This declining ecological environmental quality poses a growing threat to the ecological, environmental and socioeconomic security of local and surrounding areas (Zhang et al., 2007). Furthermore, the complexity of household energy consumption in agropastoral areas is exacerbated by multiple factors, such as droughts, rangeland degradation, active conflicts and insecurity, and constrained livestock mobility and key resource access. Household energy consumption combines the characteristics of agricultural and pastoral areas, and policymakers should have a good understanding of recent developments and models. Because the associated issues involve multiple parameters, such as the political, ethical, social, and moral dimensions, the solutions will also require a combination of multiple disciplines and more global approaches.

In recent decades, particularly in the last ten years, many studies have investigated China’s household energy consumption to quantify the energy consumption per household (Wang et al., 1996; Wang et al., 2002; Zheng et al., 2014), determine the urban-rural differences (Zhang et al., 2014; Du et al., 2015), reveal the driving forces and policy implications (Sun et al., 2014; Tian et al., 2016), examine energy-related carbon emissions and indoor environmental quality (Shan et al., 2015; Niu et al., 2014), and assess energy accessibility and livelihood (Biggs et al., 2015). For instance, Chen et al. (2006) conducted a survey of 193 rural households in Jiangxi Province in 2000 to analyze that factors that determine household energy choices and artificial investments in firewood collection (Chen et al., 2006). Another study conducted in Jiangsu Province in 2010 based on a survey of 405 households in 3 villages indicated that the household energy consumption per capita is 396.93 kgce in typical rural areas, with straw and electricity accounting for 38.73% and 32.96%, respectively, of the total energy consumption (Wang et al., 2015). Li et al. (2018) used a quantitative model to estimate the environmental and economic costs under different energy consumption structures in Gansu Province, which is located in western China (Li et al., 2018). Another survey of 1,450 households in 26 Chinese provinces conducted by Zheng et al. showed that a typical Chinese household consumed 1,426 kgce in 2012, and the researchers found that the energy sources of urban and rural households were entirely different (Zheng et al., 2014). Although many such studies have been conducted, they primarily focus on energy consumption in large cities and rural areas and do not reflect the current situation of household energy consumption in the agropastoral areas of China. At the same time, we found that research on agropastoral areas is focused on the vegetation growth

status (Halin et al., 2002), land use types (Zhou et al., 2019), rangeland management strategy （Hua et al., 2015), and food production and water resources (Lv et al., 2019). In other words, in agropastoral areas, knowledge about household energy consumption is still lacking.

Qinghai Province is one of China's four agropastoral areas, and it is often called the roof of the world because it is the highest habitat on earth. This survey mainly aims to determine the energy consumption characteristics of farmers and herders in this area. Microdata are the basis for interpreting and predicting the evolution of regional human-land relationships and for providing data support for scientific discovery and decision support for the coupling of human activities and ecological environments. Therefore, given that Qinghai Province is a region with a special humanistic and natural ecological environment (Chen et al., 2016), we establish a household energy consumption database and a system of visual statistical analysis through microscale household energy consumption research to compensate for the lack of urban and rural energy statistics at the county level and below. In our empirical study, the characteristics of human activities in Qinghai Province are further refined and provide empirical evidence for the new discipline of supplementing and developing energy geography and providing scientific support for energy transition and sustainable development in Qinghai Province.

Household income is a major economic factor influencing energy consumption decisions (Zhao et al., 2019; Jiang et al., 2019). Households with different income levels show significant differences in energy choices. When choosing energy sources, households with higher income levels are more likely to prioritize comfort. With lower income levels, however, economic efficiency is the principal influencing factor (Tian et al., 2016). Regarding the classification of household income, we refer to the income classification method adopted by the Qinghai Province Statistical Yearbook (2012), and we group household incomes and establish a typical household energy flow model. To examine how energy use at the household level changes with different levels of income in Qinghai Province, we accurately identify whether there is a difference in the energy consumption behavior of farmers and herders due to the influence of policy superposition and cultural interactions.

2. Research background

2.1 Research site

Known as Earth’s third pole, the average altitude of the Qinghai-Tibet Plateau is 4,500 m. The region has abundant natural resources, although its ecological environment is fragile. The region encompasses various ethnic cultures, but it is also economically underdeveloped. All of these factors make the Qinghai-Tibet Plateau a unique area (Ping et al., 2011). Qinghai Province is located in the northeastern area of the Qinghai-Tibet Plateau. The complex geographical environment and fragile ecological environment make the area sensitive to climate change. It is also the key construction area for China’s policies related to grazing bans and farmland to forest transformation programs. The territory has an altitude that is generally greater than 3,000 m, an annual average temperature of 2.1 °C and annual precipitation of 294 mm. The total water resources of the province are 78.57 billion cubic m, and the wind energy reserves account for 9.4% of China’s wind energy reserves. The region is the fourth largest wind field in China and has a solar radiation level of 5,800-7,400 MJ/m^2. In this respect, the area ranks second in China behind only Tibet. The altitude of the eastern part of Qinghai Province is relatively low, and the hydrothermal conditions are relatively ideal. The southern region presents a high altitude and extremely cold conditions, and the central and western regions host basins. Overall, the

area is arid. Its special geographic location as well as its unique landforms and climatic conditions have led to the formation of three types of geographic regions (from east to west): pastoral, agropastoral and agricultural.

In 2017, the population of Qinghai Province was 5.98 million and the rural population was 3.44 million. In addition, the per capita disposable income of the farmers and herders in Qinghai Province was 9,460 yuan, which is only 70.4% of the national level. The population was largely impoverished. In 2017, urban and rural residents' energy consumption was 2.816 million tons of standard coal, accounting for 6.6% of the total energy consumption in Qinghai Province. Additionally, raw coal consumption was 1.055 million tons, gasoline consumption was 259,000 tons, and power consumption was 2.74 billion kWh. Rural residents' energy consumption was 1.041 million tons of standard coal, accounting for 40% of the total energy consumption of urban and rural residents. Currently, the residents of Qinghai Province have relatively traditional energy consumption patterns. Farmers and herders lack alternative clean energy. At the same time, the energy consumption of households focuses on animal manure, which has affected the self-healing properties of the ecosystem by disrupting the nitrogen cycle. Furthermore, as a scarcely populated area, the construction costs of public energy facilities are relatively high.

2.2 Data

The study is based on data collected from a household survey regarding energy consumption in agropastoral areas of Qinghai Province in 2018. The survey follows a cluster sampling strategy. Regarding the division of pastoral, agropastoral and agricultural areas, we refer to Fei et al. (2017). The agropastoral area is distributed in the eastern and central parts of Qinghai Province, including Xunhua Salar Autonomous County, Hualong Hui Autonomous County, Haishu County, Jianzha County, Yushu City and Dulan County (Figure. 1). Three villages were selected (considering location, agricultural types, and ethnicities) in 6 counties. In each village, 11 households were selected. The sample sizes were adjusted based on the extremely low population density in some villages. In total, 132 households were sampled and 103 valid questionnaires were collected from face-to-face interviews (with an average interview time of 1 hour).

The survey mainly included the basic situation of the families, including the ethnicity, income, and educational level, the production materials of farmers and herders, and data on energy utilization, such as household energy sources, usage, and preferences. Existing household energy research focuses on household cooking and heating energy consumption (Pereira et al., 2011); however, field surveys have found that as household economic conditions improve and local infrastructure improves, farmers and herders both have increased vehicle ownership. The social activity area has expanded, and energy consumption in transportation has become an important part of household energy consumption. Therefore, this survey incorporates household transportation energy, which mainly includes gasoline and diesel, into the energy consumption statistics. Because electric vehicles have a low rate of ownership among farmers and herders and it is difficult to quantify electricity consumption, electric power is mainly based on energy consumption by household appliances and for cooking and heating. To reflect the subjective attitudes of farmers and herders regarding various energy types, this survey also includes the preferences of farmers and herders for various energy types.

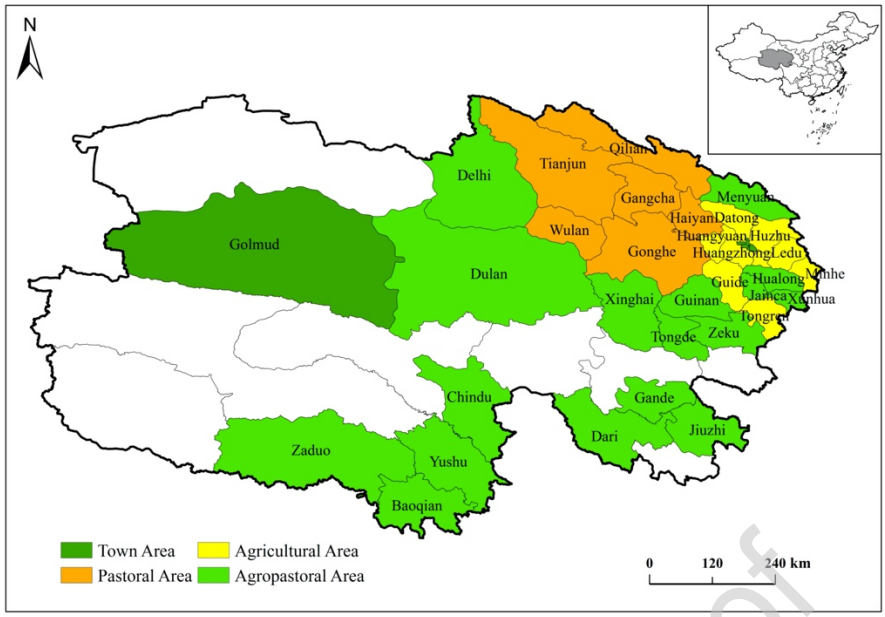

Figure. 1 Survey location map of Qinghai Province, including the surveyed counties

3. Energy consumption

What is the total amount of energy consumed by farmers and herders? Where are their energy services obtained? What are the activities of farmers and herders that consume energy? The answers to these questions about typical Chinese household energy consumption can be found in our survey data.

3.1 Measuring energy consumption

The preliminary survey results show that the household energy consumption varieties in the agropastoral areas in Qinghai Province mainly include electricity, coal, gasoline, diesel, liquified petroleum gas (LPG), firewood, straw, and animal manure. These energy consumption varieties are converted to standard coal equivalent (kgce) through multiplication by the conversion coefficients for the n energy sources. The following formula can be used to calculate the annual energy consumption of the ith family (Niu et al., 2012):

$$E_i = \sum B_i * C_i \qquad (1)$$

where Ei is the total amount of the ith energy source in standard coal, Bi is the ith energy source, and Ci is the ith energy index coal coefficient.

Household income and energy consumption are positively correlated (Jiang et al., 2019). However, due to the different livelihood strategies based on different sources of incomes of farmers and herders, there are also differences in their household energy consumption structures. Based on the per capita disposable income level of the rural areas in Qinghai Province (NBS, 2018) and combined with the per capita income of the survey area, the surveyed households are ranked according to their per capita annual income from low to high. The households are divided into five categories: low income, low-medium income, medium income, medium-high income, and high income (Table 2).

Table 1 Household income groups

	Low income	Low-medium income	Medium income	Medium-high income	High income
Per capita annual income (yuan)	1667-6400	6401-9750	9751-16667	16668-26250	26251-50000
Number of households	20	21	21	21	20

3.2 Household characteristics and income grouping

Table 2 introduces the characteristics of the survey and the surveyed households. The basic characteristics of the households in agropastoral areas are reflected in their household income, household size, nonlabor population, and educational level. The average household income increases from the low-income group to the high-income group. The income levels of the households in the low-income and high-income groups are quite different, with the high-income level 5.48-times higher than the low-income level. Household size shows a decreasing trend from low-income households to high-income households. The average low-income household size is 4.55, while the average high-income household size is 3.55. The low-income group has an average nonlabor population of 2.45, which is higher than that of the other household groups. The educational level of the residents in agropastoral areas is generally low, and the average education period of the heads of household is 5.45 years, whereas in the high-income group, the average education period is 7.35 years. The other groups show small differences, and the average household has 1.58 individuals with at least a junior high school education.

Table 2 Basic information on households with different income levels

Income group	Low income	Low-medium income	Medium income	Medium-high income	High income
Household income (yuan)	21725	35810	55143	84333	119000
Household size (persons)	4.55	4.38	4.33	4.00	3.55
Nonlabor population	2.45	2.14	2.19	1.67	1.85
Educational level of the head of household (persons)	4.05	4.62	3.90	3.29	7.35
Higher than junior high school education (persons)	2.05	1.57	1.19	1.52	1.55
Age of the head of household	55.05	48.19	50.67	51.86	51.00
Household cultivated area (mu)	6.34	8.71	4.48	3.10	0.00
Household grass area (mu)	100.7	11.10	278.81	537.14	470.00

3.3 Energy consumption structure

The household energy sources in the study area include electricity, coal, gasoline, diesel, LPG, firewood, straw and animal manure. Coal, animal manure and firewood are the main energy sources, accounting for 21.97%, 21.11% and 16.7% of the energy sources used, respectively, while electricity, diesel, and LPG are less important energy sources, accounting for 3.17%, 3.56%, and 4.62% of the energy sources used, respectively. The per capita annual energy consumption is 1,245 kgce, which is twice that of the Gannan agropastoral area (618.95 kgce) of Gansu Province (Li et al., 201) and higher than that of the agropastoral area (744.04 kgce) in northwestern Yunnan Province (Xin et al., 2012) but lower than the per capita energy consumption level of the rural areas in Qinghai Province (1,530 kgce). The energy consumption

structure of the agropastoral areas in Qinghai Province is similar to that of the agropastoral areas in the Gannan Plateau. Biomass energy consumption, such as animal manure, firewood, and straw, is relatively high. Compared with the agropastoral area in northwestern Yunnan Province (Xin et al., 2012), the proportion of solar energy utilization in the agropastoral area of Qinghai Province is small.

We find that the proportion of noncommercial energy consumption decreases with increasing household income. The proportions from the low-income group to the high-income group are 64.33%, 62.65%, 50.92%, 49.85%, and 37.14%. From the perspective of individual energy sources, animal manure accounts for the largest proportion at 13.34% of the low-medium-income group, while the other four groups account for more than 20%. The share of firewood consumption is second only to that of animal manure, and the consumption proportions are ranked as follows: low-income households > low-medium-income households > medium-income households > medium-high-income households > high-income households. The proportion of straw consumption is the smallest, and the proportion of straw consumption among the five types of households is quite different. The proportion of low-income households is the largest (24.29%), while that of medium-income households is the smallest (9.45%) because high-income households have more grassland areas and less arable land compared with low-income households; thus, there are fewer straw resources. The agropastoral area has regional advantages, and the availability of traditional biomass energy is high, which makes the transition to modern clean energy difficult. We found that in the agropastoral area, because it is closer to the pastoral area, the nearest village is only 10 km away from the pastoral area. The residents choose to buy animal manure from herders as their household energy source, and the price is 0.24 yuan/kg, which is lower than the prices of coal and electricity, thus resulting in long-term traditional biomass energy as the main source of energy for cooking and heating.

The proportion of commodity energy consumption has increased with the increase in household income. The proportions from low-income to high-income households are 35.67%, 37.35%, 49.08%, 50.15%, and 62.6%. Among the five types of households, coal consumption represents the largest type of consumption, and the proportions of coal consumption in the five types of households are almost the same. Medium-income households have the largest proportion (28.16%), while low-income households have the smallest proportion (17.08%). The ‘returning farmland to forest’ (RFF) policy has been widely praised as a major contributor to China’s dramatic increase in forest cover from perhaps as low as 8% in 1960 to approximately 21% in 2013 (Trac et al., 2013). The implementation of the RFF policy has led to a reduction in the amount of arable land in agropastoral areas, and the production of straw is insufficient to meet the daily needs of farmers. Due to the deterioration of grassland ecology in western China, since 2003, the Chinese government has implemented the ‘returning grazing land to grassland project’ (RGLGP) in areas with degraded grassland, and it plans to support the project through 2020 (Shao et al., 2016). Due to the implementation of the RGLGP, livestock farming in pastoral areas is reduced, animal manure production is insufficient to meet daily needs, and households living near coal mining areas are gradually using coal to replace firewood and animal manure as an important energy source for cooking and heating.

The electricity consumption of medium-income households is 4.08%, and that of low-income households is low at less than 3%. Although the penetration rate of electricity in the survey area reaches 97%; in most households, electricity is not used for heating and cooking

but only for home appliances; thus, electricity consumption accounts for a relatively small proportion. The proportions of LPG consumption are ordered as follows: high-income households > medium-high-income households > low-medium-income households > low-income households > medium-income households. The consumption of LPG is low because farmers and herders believe that the price of LPG is too high at approximately 9 yuan/kg. Due to such high prices, the proportion of LPG consumption presents a nearly 10-fold difference between high-income and low-income households. The proportion is the smallest among low-medium-income households (1.10%), while the proportion is largest among the high-income households (10.12%).

Clean energy consumption accounts for a small proportion of the total because farmers and herders believe that solar cookers are unevenly heated; thus, they are often discarded. Some residents use solar panels to generate electricity only for lighting. For example, in the village of Hualong County, where the Hui nationality is concentrated, although 80% of the residents have installed solar energy stoves, solar cookers are discarded because they are easily damaged and because the heat concentration is uneven and unstable. The biogas and natural gas utilization rates in the research area are less than 4%.

The results show that low-income households prefer to use non-commodity energy, such as firewood, straw, and animal manure as their main energy sources, while higher-income households prefer high-quality commodity energy, such as coal, gasoline, and LPG. High-income households are more likely to achieve a clean energy transition, and this result is similar to the findings of Damette et al. (2018) (Table 3).

Table 3 Energy consumption structure of households with different income levels

Income group	Low income		Low-medium income		Medium income		Medium-high income		High income	
Energy	kgce	%	kgce	%	Kgce	%	kgce	%	kgce	%
Electricity	3300	3.29	2770	2.44	3879	4.08	3823	3.30	3168	2.90
Coal	17143	17.08	25315	22.29	26786	28.16	24800	21.42	23286	21.34
Gasoline	9304	9.27	11311	9.96	8694	9.14	16765	14.48	27535	25.23
Diesel	3097	3.09	1786	1.57	4061	4.27	6488	5.61	3571	3.27
LPG	2962	2.95	1245	1.10	3257	3.42	6171	5.33	11040	10.12
Firewood	24503	24.41	28418	25.02	17625	18.53	11147	9.63	7468	6.84
Straw	14658	14.60	27593	24.29	8984	9.45	18641	16.10	10643	9.75
Animal manure	25408	25.31	15148	13.34	21823	22.94	27920	24.12	22428	20.55

3.4 Quantification of household energy use

Household energy consumption refers to all the different kinds of energy used to meet the requirements of daily life, including cooking, heating, transportation, and home appliances. In the agropastoral areas of Qinghai Province, the energy used for space heating accounts for the greatest proportion of total residential energy use (52%), followed by cooking (29%), transportation (17%), and home appliances (2%).

Among the energy use rates in the survey area, electricity usage is the highest (99.0%), and it is mainly used for lighting and home appliances (85.4%). Moreover, 43.7% and 11.7% of all households use electricity for daily cooking and heating, respectively. The use rate of coal is 85.4%, with 74.8% of all households using coal for heating and 32.0% using coal for

cooking. The use rate of gasoline and diesel is 89.9%, and they are mainly used for transportation. The usage rates of firewood, straw and animal manure are 59.2%, 56.0%, and 74.8%, respectively, and they are mainly for heating and cooking. LPG is used by 38.4% of all households as a replacement energy source for cooking, and 38.9% of all households use solar energy, mainly solar panels, to generate electricity for lighting.

For the average household, 2,020 kgce of energy is used for cooking. Firewood, straw, LPG, animal manure, and coal are mainly used for cooking. More specifically, each household consumes an average of 1,296 kg (704 kgce) of straw and 1,213 kg (693 kgce) of firewood for cooking. In terms of the other energy sources, each household consumes an average of 140 kg (240 kgce) of LPG, 436 kg (219 kgce) of animal manure and 159 kg (114 kgce) of coal for cooking.

On average, each household uses 2,160 kgce for space heating. Additionally, each household consumes 1,435 kg (1025 kgce) of coal per year for heating. With increasing income, household heating has gradually shifted from the practice of wearing more clothes and sleeping with hot water bottles to the practice of using coal stoves. Coal purchases for heating and cooking account for 1.52% of total annual household income. China has established heating systems in urban and subsidized urban residential areas for heating. However, the heating of rural residents is not included in the government's public expenditure. Heating depends on individual behavior. Animal manure, firewood, and straw are also the main energy sources for heating. On average, each household consumes 1,751 kg (876 kgce) of animal manure, 303 kg (173 kgce) of firewood and 144 kg (78 kgce) of straw.

The average distance between a typical household and the nearest city or downtown, school, and hospital or clinic is 5, 3.4, and 3 km, respectively. In the households surveyed, the average frequency of travel per member is 0.45 trips. However, public transportation can barely meet residents' daily travel needs. To meet a subset of those needs, 96% of all households use private transportation and consume gasoline. The private vehicle ownership rate is higher than that of the average Chinese household (93%). Each household consumes approximately 695 L (74 kgce) of gasoline per year for transportation, and 41% of all households use agricultural vehicles, such as tractors, to transport crops. The average household consumes 373 L (452 kgce) of diesel per year, and 4.9% of all households use electric vehicles as a means of transportation. The annual energy consumption of each household is approximately 1,200 kgce.

Table 4 introduces the use of household appliances in the surveyed households. The usage rates of electric lighting, washing machines, refrigerators, electric kettles, and televisions are more than 90%. On average, each household uses 1,338 kWh (164 kgce) of electricity per year, costing approximately 575 yuan and accounting for 0.9% of total household annual income.

Table 4 Household appliance ownership

	Refrigerator	Television	Electric kettle	Induction cooker	Microwave oven	Rice cooker	Electric lighting	Washing machine
Usage rate	92.2%	92.2%	50.5%	28.2%	9.7%	29.1%	94.2%	97.1%

4. Household attitude toward energy

The design of energy policies and interventions requires in-depth studies of household energy consumption perceptions and motivations. To understand households' attitudes toward

various energy types, we investigated the attitudes of farmers and herders toward various energy sources, such as electricity, coal, gasoline, diesel, LPG, firewood, straw, biogas, animal manure, natural gas, and solar energy. In exploring the attitudes of farmers and herders, we found that the energy sources from most important to less important are as follows: electricity, coal, gasoline, diesel, animal manure, natural gas, LPG, solar energy, firewood, straw, and biogas. Electricity is considered to be the most important energy source in all households, possibly because electricity plays an important role in lighting, refrigerators, televisions, and washing machines. Coal, as the main energy source for heating and cooking, is also considered to be of great importance. For farmers and herders, gasoline and diesel are the main energy sources for transportation; therefore, they are also of great importance. The importance of LPG shows an increasing trend with increasing household income, while the importance of firewood and straw shows a decreasing trend with increasing household income. Biogas and solar energy are of low importance to farmers and herders because of their low usage rate.

5. Residential energy flow chart in agropastoral areas

Taking the household as the basic unit and then establishing a typical household energy flow model (Figure.2), we observe the changes in the form, function, and value of energy in the transformation process from the original state to consumption and abandonment. Based on Table 3, we assessed the energy consumption levels of individual households. We calculated the energy consumption of different types and uses from low- to high-income households and computed the average energy consumption process of low-, middle- and high-income households. We applied the e!Sankey Pro 4.5.3 software tool, which can be used to draw energy flow charts and Sankey diagrams as shown in Figs. 3, 4, and 5.

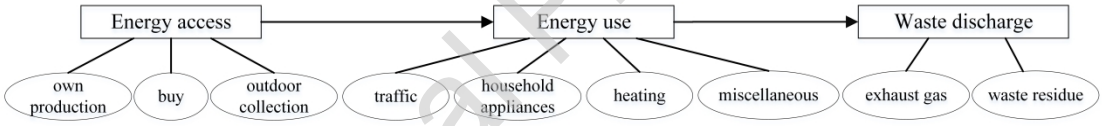

Figure. 2 Abstract model of household energy material flow

In low-income households, the main sources of energy are firewood, straw, livestock manure and coal. Commodity energy consumption accounts for 27.0%. Coal and animal manure are used for heating, while firewood, straw, and LPG are used for cooking. These households annually consume 5,110 kg (2,918 kgce) of firewood, 1,825 kg (991 kgce) of straw, 1,825 kg (913 kgce) of animal manure, and approximately 1,000 kg (714 kgce) of coal. Low-income households consume 6,615 kgce of energy per year, thereby producing 482 kg of ash and 146 kg of coal ash as well as waste gas (Figure. 3).

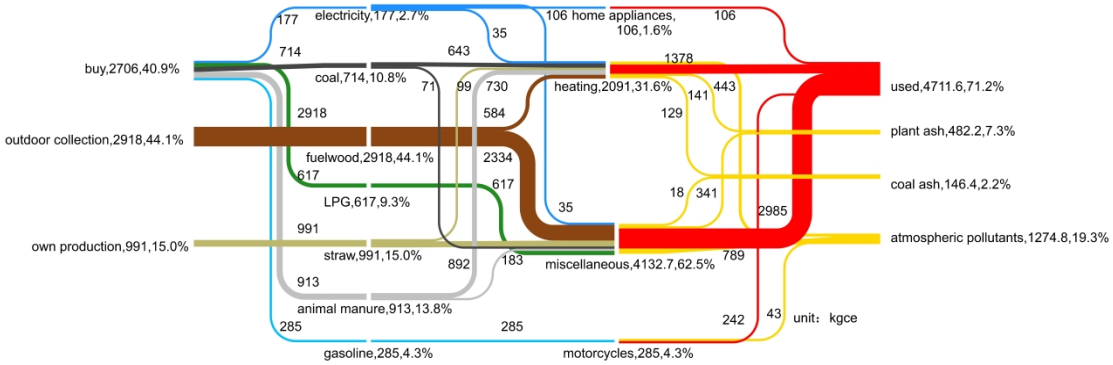

Figure. 3 Household A energy flow model

In medium-income households, firewood, coal and animal manure are the main sources of household energy. Commodity energy consumption accounts for 42.7%. Medium-income households use 4,560 kg (2,604 kgce) of firewood, 2,000 kg (1,429 kgce) of coal, and 1,825 kg (913 kgce) of animal manure per year. Among these sources, coal and animal manure are used for heating while firewood is used for cooking. The household energy consumption is approximately 6,137 kgce/year, thereby producing 357 kg of coal ash, 352 kg of ash, and waste gas (Figure. 4).

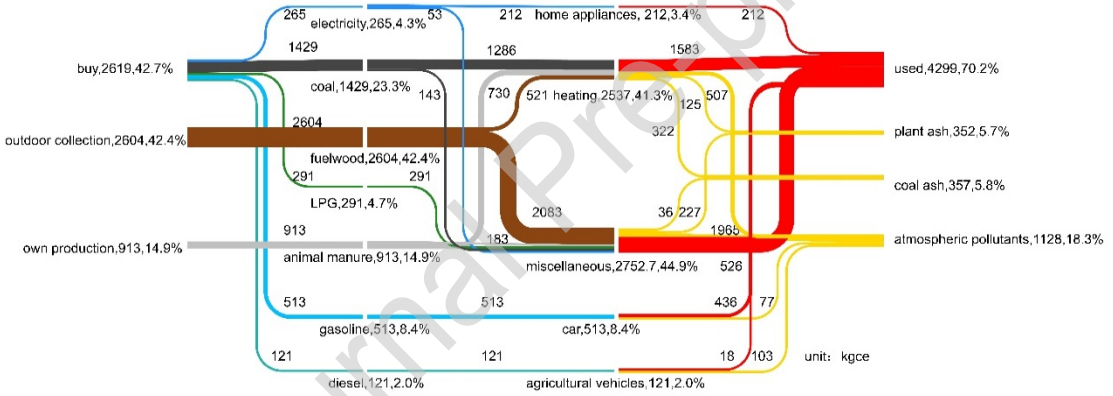

Figure. 4 Household B energy flow model

In high-income households, animal manure, coal, and straw are the main household energy sources. Commodity energy consumption accounts for 47.6%. High-income households use 4,500 kg (2,250 kgce) of animal manure, 2,000 kg (1,429 kgce) of coal, and 1,300 kg (706 kgce) of straw per year. Animal manure and coal are used for heating, while straw and LPG are used for cooking. Moreover, 357 kg of coal ash and 323 kg of ash are produced due to household energy consumption (Figure. 5).

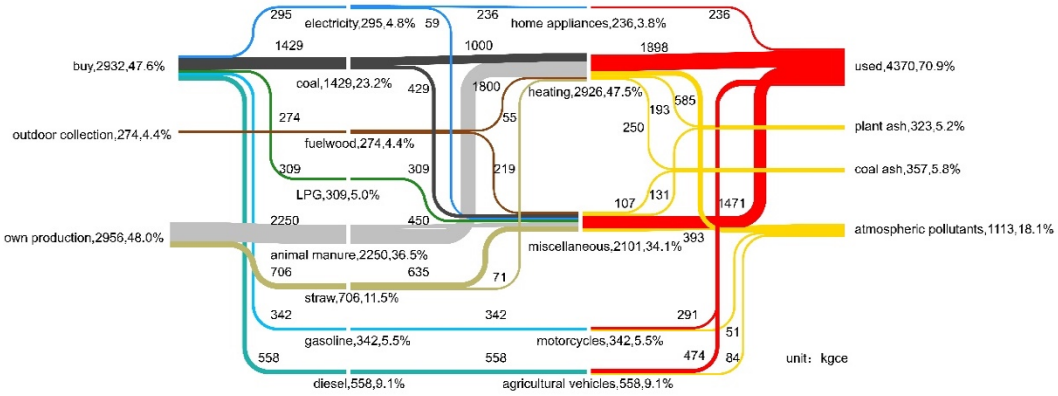

Figure. 5 Household C energy flow model

6. Discussion

We found that there are striking differences among these household energy material flow models. From low-income households to high-income households, the types of household energy sources increase, the consumption of energy increases, and the energy flows become more frequent. Compared with low-income households, the proportion of commodity energy consumption increases and the consumption of coal, gasoline, diesel, and LPG increases in high-income households. More than 70% of energy is eventually converted into heat or mechanical energy, while approximately 30% is converted into grass ash, coal ash, and atmospheric pollutants and is not directly used.

In household A, B, and C, the proportion of energy used for heating is 31.6%, 41.3%, and 47.5%, respectively, thus showing an increasing trend. This finding is consistent with the research by Chen et al., who show that households with higher incomes demand higher housing comfort levels (Chen et al., 2006); thus, the proportion of household energy consumption for heating increases. As incomes increase, household heating energy tends to be cleaner, more efficient, and more convenient. The proportions of energy consumption for household appliances and transportation also increase with the increase in household income, whereas the proportion of energy consumption for cooking decreases. Moll et al. (2005) compared the average household energy requirements for different household income groups and found that low-income households use larger shares of their household budget for heating and electricity and smaller shares for motor fuel, transportation, and recreation. In households with the same income level, household size is negatively correlated with per capita energy consumption. Households with fewer members tend to use more energy per capita than do larger households. Similar results were reported by Zhou et al. (2009) in rural households in Jilin Province and Jiangsu Province; for every additional member, per capita energy consumption was reduced by 0.458 kgce and 0.243 kgce, respectively.

For all three types of households, those who lived in a high-income household tend to consume less energy in general due to their educational level. Similar results were reported by Baiocchi et al. (2010) in the UK, where higher educational levels are linked to lower direct and embedded household emissions. For example, in Desheng Village, Hainan Tibetan Autonomous Prefecture, two out of every five members of a household have undergraduate degrees. These members will guide the other household members in carrying out energy-saving consumption measures, such as the use of animal manure to heat insulation kettles. In terms of

space heating, iron pipelines are used inside and heat is transmitted from room to room, thus improving the energy utilization efficiency.

Affected by both the RFF policy and the RGLGP, farmers and herders have moved from pastoral areas and agriculture areas to counties. On the one hand, farmers and herders have reduced their biomass energy consumption, such as livestock manure and straw, and increased their commodity energy consumption, such as coal and electricity; on the other hand, they have increased the proportion of transportation energy consumption among their household energy consumption. Rural residents mainly use small cars, and herders mainly use motorcycles. As household incomes increase, household energy consumption for transportation also increases.

Comparing the energy flows of Tibetan and Hui medium-income households, we find that households of different cultural backgrounds have different characteristics in energy consumption. This phenomenon is mainly due to the different cultural attributes of household production and lifestyle, which lead to differences in the demand for energy consumption. For example, the proportion of commodity energy consumption of Hui households (42.7%) is higher than that of Tibetan households (39.9%), whereas the proportion of noncommodity energy consumption (57.3%) is lower than that of Tibetan households (60.1%) and the proportion of clean energy consumption (4.3) %) is also lower than that of Tibetan households (7.2%). From the perspective of single energy sources, coal is the main source of energy for the two types of ethnic households, with Hui households tending to use firewood and straw and Tibetan households tending to use animal manure. In terms of energy use, the proportion of energy used by Hui households (44.9%) is lower than that used by Tibetan households (49.5%), which may be affected by the Islamic culture of the Hui people, who cook less during the period of Ramadan.

7. Conclusions and policy implications

The detailed data set of this paper is mainly obtained from 103 surveyed households, and the energy consumption of China's agricultural and pastoral areas in 2017-2018 is summarized. Energy consumption is estimated in terms of six types of energy (such as firewood, coal, and animal manure) and four types of end-user activities (cooking, powering home appliances, space heating, and using transportation). For a better summary and comparative analysis, standard coal equivalent represents the unit for all energy sources. Additionally, the typical Chinese family is analyzed in the form of an energy flow chart.

Overall, the average household energy consumption in the survey area is 1,245 kg. The major energy source for a typical household is coal (21.97%), followed by animal manure (21.11%) and firewood (16.7%). Heating is the most important use, followed by cooking. Electricity usage is the highest but accounts for only 3.2% of the energy consumption structure, which is lower than the average proportion in China (10.7%). Electricity is mainly used for household appliances, although the variety of electrical appliances is low, and they are mainly used to meet basic living needs. The use of solar energy, biogas and other clean energy sources is low because of low-technology conditions, thus making it impossible for such sources to meet daily needs. Compared with the agropastoral areas in the Gannan Plateau and northwestern Yunnan Province, we found that the energy consumption structure of Qinghai Province is similar to that of the Gannan Plateau and has a smaller proportion of solar energy utilization than that of northwestern Yunnan. Affected by agricultural and animal husbandry policies, household energy consumption has shifted from a structure dominated by traditional

biomass, such as animal manure and straw, to a multi-energy combination structure dominated by coal. Due to their different cultural backgrounds, households have different levels of environmental awareness and consumption concepts, which impact household energy consumption.

The policy implications of our results mainly involve three aspects. First, our data and analysis reveal an overall picture that can help policymakers understand the current household energy needs of the farmers and herders in the Qinghai-Tibet Plateau. Affected by the RFF policy and the RGLGP, modern commercial energy will replace traditional biomass fuels from rural to urban areas if policymakers predict the variability of these plans, produce more accurate predictions of energy demands, and generate more scientific predictions of energy-related infrastructure investments.

Second, the key opportunities for energy management are determined by our results. For example, as shown in the energy flow chart, space heating accounts for half of the energy demand, with coal, firewood and animal manure representing the main fuels. Because municipal heating stations provide heating services in most areas, this situation creates opportunities for more efficient heat generation to save energy and to reduce the heat loss rates of pipelines and other measures.

Third, our dataset provides a basis for evaluating household energy consumption for transportation. We find that due to the gradual popularization of modern vehicles, such as cars, agricultural vehicles, and battery-powered vehicles, transportation energy has become the main growth area of household energy consumption and future growth trends are estimated. Therefore, in future energy policies, the focus must be shifted to the transportation sector.

Our initial results leave space for future research. The sample describes household energy consumption only in an agropastoral area, and other areas remain to be researched, such as pastoral and agricultural areas. In addition, household energy consumption is a very complicated process. To abstract it into a visual material flow model, the energy flow model of several households in this paper has simplified it to some extent. The emission coefficient of atmospheric pollutants, which is used to calculate the proportion of ash used in the production of ash, coal ash and atmospheric pollutants after the use of various energy sources, refers to the results of relevant studies but does not consider the differences in energy quality.

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- The study is based on household survey during 2017-2018 in Qinghai, China.
- A household energy flow model is applied to examine household energy consumption.
- The proportion of noncommercial energy use in Qinghai's agropastoral area is 53%.
- Household energy use is affected by land policies, cultural backgrounds, and income.