Material Flow Analysis of Household Energy Consumption in Urban Communities on the Qinghai Plateau: A Case Study of Xining City (Postprint)

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Abstract

In the superimposed context of the post-industrial era and the post-pandemic era, urban household energy consumption continues to increase, making households a major contributor to carbon emissions from energy consumption. As a plateau city, Xining is a crucial stronghold for ecological security, and research analyzing its household energy consumption plays a vital role in China's ecological civilization construction. Based on 2021 field survey data combined with an Ordinary Least Squares (OLS) regression model, this study explores household energy consumption characteristics and influencing factors by constructing household energy flows, and visualizes the entire process of household energy consumption under different income scenarios. The results show that: (1) The annual per capita energy consumption of urban households in Xining City is 461.57 kgce·a-1. (2) In terms of energy use, the per capita heating energy consumption of urban households in Xining City is 307.52 kgce·a-1, which constitutes the primary source of household energy consumption, while washing machines among large household appliances have the lowest energy consumption. (3) Total household income at year-end is the core factor influencing per capita annual energy consumption in Xining households. (4) High-income households exhibit high per capita energy consumption; however, as household income levels increase, heating energy consumption decreases accordingly. Based on these findings, the study recommends increasing clean energy supply to residents, enhancing all residents' awareness of renewable energy, and intensifying energy conservation publicity and autonomous energy-saving awareness among middle- and high-income populations. By formulating energy policies tailored to local conditions, we can advance the process of sustainable energy development in China.

Full Text

Household Energy Consumption in Urban Communities of the Qinghai Plateau Based on Material Flow: A Case Study of Xining City

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Abstract: Against the backdrop of the overlapping post-industrial and post-pandemic eras, household energy consumption in urban areas continues to increase, making households the primary contributor to carbon emissions from energy use. Xining City, a plateau city that serves as a critical guardian of ecological security, represents an important case for analyzing household energy consumption in support of China's ecological civilization construction. Based on 2021 field survey data and using the Ordinary Least Squares (OLS) regression model, this study explores household energy consumption characteristics and influencing factors in Xining by constructing household energy flows and visualizing the complete consumption process across different income levels. The results show that: (1) The annual per capita energy consumption of urban households in Xining is 461.57 $\mathrm{kgce} \cdot \mathrm{a}^{-1}$. (2) In terms of energy use, heating accounts for the largest share at 307.52 $\mathrm{kgce} \cdot \mathrm{a}^{-1}$ per capita, representing the primary source of household energy consumption, while washing machines consume the least energy among large household appliances. (3) Total year-end household income is the core factor influencing per capita annual energy consumption. (4) High-income households have greater per capita energy consumption, but heating energy consumption decreases as household income rises. Based on these findings, we recommend increasing the supply of clean energy to residents, enhancing awareness of renewable energy among all residents, and intensifying energy conservation promotion and autonomous energy-saving consciousness among middle- and high-income populations. By formulating energy policies tailored to local conditions, we can advance China's sustainable energy development.

Keywords: household energy consumption; plateau towns; influencing factors; OLS model; Xining City

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1 Introduction

With the rapid development of post-industrialization and new urbanization, household energy consumption ranks second only to the industrial sector. Households account for 29% of global energy consumption [1], and in the same year, China's household energy consumption reached 12.66% of national energy consumption, amounting to 6.17×10^{8} tce [2], making households a major contributor to carbon emissions. Given that behavioral patterns and lifestyles significantly influence household energy consumption, understanding the current state of household energy consumption and its driving factors has become a primary concern for governments and international organizations, particularly under the dual pressures of the pandemic and post-industrial era [3].

From a geographical perspective, interactions across spatial scales shape the spatial structure of household energy consumption, with distinct patterns emerging at each scale. Scholars have explored scale conversion and integration methods, conducting empirical analyses from macro, meso, and micro perspectives. At the global scale, the Intergovernmental Panel on Climate Change (IPCC) [4] analyzed household energy consumption and carbon emissions in nearly 60 countries, finding that global household energy consumption increased by 14%, primarily driven by developing countries. At the national scale, studies comparing 10 European countries revealed substantial differences in direct and indirect energy consumption within household sectors [5]. China is currently undergoing the largest urbanization process in history, with an expected urban population exceeding 70% by 2030, which will inevitably generate more residential energy consumption and exert long-term pressure on urban energy consumption revolution [6]. Given the varying levels and characteristics of cities in climate change action, understanding urban residents' energy consumption patterns and future emission reduction potential is crucial [7].

At the regional (provincial) scale, Zheng et al. [8] used national household energy consumption survey data to identify significant differences in energy consumption patterns between northern and southern China. At the urban-rural scale, most research has focused on rural areas, with scholars conducting surveys in Shanxi, Guizhou, Zhejiang, and other provinces, revealing regional variations in both the structure and quantity of urban and rural household energy consumption [9-11]. Although previous studies on influencing factors have primarily focused on socioeconomic factors (income, population, housing area), behavioral and cultural factors (behavior, ethnicity), and external factors (government policy and energy availability) [12-14], no consensus has been reached. Economic studies using labor force survey data and field research have consistently found that income level, permanent population, energy prices, and housing area are main factors affecting household energy consumption in both rural and urban areas [10,13-17]. Behavioral and cultural research has shown differences in energy consumption between Han and ethnic minority households [18]. Studies from China's three major economic belts and Singaporean resident experiments demonstrate that social norms, policies, regulations, economic costs, publicity and education, technological maturity, and information feedback can promote energy-saving behavior and suppress high household energy consumption [19-20]. Additionally, research has found that India's rigid caste system and relatively low status of women create gender differences in household energy consumption [21].

Overall, while domestic and international scholars have analyzed heterogeneity in household energy consumption across different scales and achieved remarkable results in exploring how various factors influence consumption patterns, there remains a relative lack of in-depth micro-scale analysis at the community level, particularly in high-altitude regions where micro-data is difficult to obtain. Household energy consumption activities, as a typical human-environment interaction, represent a major trend in refined energy geography research. Urban space encompasses neighborhoods, communities, and social areas [22], and examining urban geographical space at the community scale is significant for understanding the overall spatial characteristics of household energy consumption.

As rapid urbanization in northwestern China poses severe challenges to local ecological environments, Lu et al. [23] evaluated Qinghai Province's resource-environment efficiency in 2017, finding its average value below 0.5, indicating low efficiency status that hinders its goal of building an ecological civilization highland. As a representative plateau city and critical guardian of China's ecological security, Xining was selected for this study. Through field survey data, we explore the particularities of urban household energy consumption and its influencing factors in plateau regions, providing scientific reference for energy transition in the social domain.

2 Study Area

Xining City, the capital of Qinghai Province, is located in northwestern China, eastern Qinghai Province, in the Huangshui River valley basin, with an average elevation of 3130 m. Xining has a continental plateau semi-arid climate with annual sunshine hours of 1939.7 h, average temperature of 7.6 ℃, maximum temperature of 34.6 ℃, and minimum temperature of -18.9 ℃. The city covers 7.66$\times10^{3}$ km^2 and includes Chengdong, Chengzhong, Chengxi, Chengbei, Huangzhong districts, Huangyuan County, and Datong Hui and Tu Autonomous County. By the end of 2021, Xining's urban permanent population reached 1.96$\times10^{6}$, accounting for 79.33$\times10^{4}$ yuan, with per capita consumption expenditure at 2.21$\times10^{4}$ yuan. Energy consumption shows an upward trend, increasing from 8.75$\times10^{6}$ tce in 2015 to 1.17$\times10^{7}$ tce in 2020, a 33.72% increase [24]. Xining is rich in clean energy resources but has weak basic energy infrastructure. Against the backdrop of Qinghai Province's efforts to build a national clean energy industry highland, Xining serves as a representative case for household energy consumption research.

3 Data and Methods

3.1 Data Sources Data on urban household energy consumption in Xining primarily came from field surveys. To understand the current status and challenges of household energy consumption in Xining's main urban districts and county towns, the research team conducted field surveys in July 2021 using interview and sampling methods [25], covering five districts and two counties. The survey targeted households as the basic unit, distributing 600 questionnaires and recovering 573. After data preprocessing, 545 valid questionnaires were obtained (95.28% validity). Sample information included household and economic characteristics (Table 1). Figure 1 shows the research area and sample point distribution.

3.2 Methods

3.2.1 Household Energy Consumption Accounting Method Survey data were processed to calculate energy consumption across Xining's five districts and two counties. This study adopted the household energy estimation algorithm from the China Residential Energy Consumption Survey (CRECS) [26], calculating actual consumption of each fuel type based on corresponding equipment parameters (power, combustion rate, energy efficiency rating) and user consumption characteristics (daily usage frequency and duration). Energy consumption was then converted to standard coal equivalent using coefficients from the *General Rules for Calculation of Comprehensive Energy Consumption* (GB/T2589-2020) [27]. The specific calculation method is as follows:

$$\text{Energy} = \Sigma \ \Sigma \ \text{Energy} \times \text{coef}$$

where Energy is the energy consumption of household i (kgce); M represents different household energy consumption activities (e.g., lighting, cooking); N represents different energy types; Energy is the physical consumption of energy type n by household i for activity m; and coef is the conversion coefficient for different energy types.

The selection of conversion coefficients directly affects total energy consumption calculations. This study used reference coefficients from GB/T2589-2020 (Table 2).

3.2.2 Model Construction and Variable Selection Ordinary Least Squares (OLS) is a linear regression model suitable for studying linear relationships between per capita household energy consumption and influencing factors. To properly interpret OLS coefficients, data must satisfy normality, independence, linear correlation, and homoscedasticity assumptions. The linear regression model is expressed as:

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 +$$

where y is per capita energy consumption of household t; x_1 is total year-end household income; x_2 is education level; x_3 is number of household laborers; α is the constant term; β_1, β_2, β_3 are regression coefficients; and is the random error term.

Variable Selection: Previous literature indicates that household energy consumption is primarily influenced by household and economic characteristics [12-14]. Therefore, this study selected total year-end household income, number of household laborers, and education level as independent variables. Total year-end household income and number of laborers are continuous variables, while education level is categorical. During urbanization, household population structure shows an inverted U-shaped relationship with per capita residential energy consumption: early urbanization suppresses consumption, but consumption increases with further urbanization development. The number of household laborers negatively correlates with energy consumption, as more laborers reduce time spent at home. Total year-end household income positively correlates with consumption, as residents adjust energy use based on income and resource prices, maintaining a long-term stable relationship. Education level negatively correlates with consumption, as higher education strengthens energy-saving awareness, alleviating household energy consumption. To ensure objectivity and rationality, both per capita household energy consumption and annual household income were log-transformed for regression analysis. Table 3 provides variable definitions and descriptive statistics.

4 Results and Analysis

4.1 Household Energy Consumption by End Use In 2021, Xining's urban households consumed 461.56 kgce · a^{-1} per capita. By region, Huangyuan County had the highest consumption at 631.12 kgce · a^{-1}, followed by main urban districts (Chengdong, Chengzhong, Chengxi, Chengbei, Huangzhong) at 466.56 kgce · a^{-1}, and Datong County at 398.26 kgce · a^{-1}.

In terms of energy use, heating energy consumption dominates across all districts and counties at 307.52 kgce · a^{-1} per capita, accounting for 66.62% of total consumption, followed by cooking (74.56 kgce · a^{-1}, 16.15%), water heaters (68.83 kgce · a^{-1}, 14.91%), refrigerators (10.27 kgce · a^{-1}, 2.23%), televisions (5.85 kgce · a^{-1}, 1.27%), lighting (2.17 kgce · a^{-1}, 0.47%), and washing machines (0.44 kgce · a^{-1}, 0.10%) (Figure 2, Table 4). Survey results show that tenant households prefer liquefied petroleum gas for cooking to reduce expenses. Water heater energy consumption is 60.36 kgce · a^{-1}, with electricity accounting for 87.7% and natural gas for 12.3%. Refrigerator consumption is 10.27 kgce · a^{-1}, washing machines 2.17 kgce · a^{-1}, and televisions 5.85 kgce · a^{-1}. Washing machines show the smallest share at 0.10%, with most households using them weekly; only a few households with young children use them daily.

Xining's urban household energy consumption comprises four categories: kitchen equipment, large household appliances, heating equipment, and lighting. Kitchen equipment is dominated by stoves, while large appliances include refrigerators, washing machines, televisions, and water heaters.

Heating and kitchen equipment constitute important components of household energy consumption (Figure 2). Main urban districts consume 315.42 kgce $\cdot$ a^{-1} for heating (67.61% of total), Datong County 262.04 kgce $\cdot$ a^{-1} (65.79%), and Huangyuan County 401.72 kgce $\cdot$ a^{-1} (63.65%). Natural gas is the primary heating fuel, accounting for 100% of heating energy. Cooking consumption is 68.83 kgce $\cdot$ a^{-1}, with natural gas (60.21%), electricity (33.81%), and liquefied petroleum gas (5.98%) as main sources. Huangyuan County leads in cooking consumption at 141.17 kgce $\cdot$ a^{-1} (22.37% of total), while Datong County has the highest shares for water heaters, refrigerators, and lighting at 16.37%, 3.10%, and 1.32% respectively (Table 5).

4.2 Regression Results Based on the OLS model, we identified factors influencing per capita household energy consumption in Xining (Table 6). In Model 1, total year-end household income shows a negative effect: a 1% income increase reduces per capita consumption by 39.81%. In Model 2, adding education level maintains the negative income effect, with each 1% income increase reducing consumption by 24.65%. In Model 3, adding number of laborers preserves the negative income relationship, with each 1% income increase reducing consumption by 22.10%. Thus, total year-end household income is the key factor influencing per capita energy consumption.

4.3 Energy Flow Construction by Household Income Given the significant income effect identified above, we further analyzed how different income levels affect energy consumption. Based on the *Qinghai Statistical Yearbook* [28], we sorted sample households by per capita annual income into low, middle, middle-high, and high-income groups (Table 7). Using average consumption values for each group, we selected representative households to construct energy flow models [29] using e!Sankey software.

Household A (Low-income): Per capita annual income of 1.13×10^{4} yuan, household size of 3, 1 laborer, respondent age 52, total energy consumption 2099.6 kgce $\cdot$ a^{-1}. Natural gas accounts for 92.3% of consumption, primarily for heating; electricity accounts for only 7.7%, with water heaters using 66.9% of electricity, washing machines 1.2%, and televisions 0.6%.

Household B (Middle-income): Per capita annual income of 2.84×10^{4} yuan, household size of 4, 2 laborers, respondent age 46, total consumption 2841.3 kgce $\cdot$ a^{-1}. This household uses three energy types: electricity, solar, and natural gas. Natural gas accounts for 63.5% of consumption, with heating using 85.3% of gas; solar accounts for 33.3%, mainly for water heating; electricity accounts for 48.4%, with refrigerators using 48.4% of electricity, water heaters 13.1%, and televisions 2.3%.

Household C (High-income): Per capita annual income of 6.67×10^{4}

yuan, household size of 3, 2 laborers, respondent age 42, total consumption 3218.0 kgce • a^{-1}. This household uses two energy types: electricity and natural gas. Natural gas accounts for 97.3% of consumption, used for stoves, water heaters, and heating, with water heaters using 57.8% of gas and heating 29.5%; electricity accounts for 2.7%, with televisions using 12.3% of electricity and washing machines 1.4%.

As income increases, household energy types diversify and consumption quantities rise, with the proportion of large appliances increasing. However, heating energy consumption decreases with rising income, as high-income households prefer self-heating systems that allow autonomous temperature control, reducing waste from overheating in centralized heating systems.

5 Discussion

As critical guardians of China's ecological security, plateau cities like Xining require thorough exploration of household energy consumption to support national ecological civilization construction. Based on our findings, we propose the following recommendations:

First, as China's first national clean energy demonstration province, Qinghai has significant potential for clean energy industry development, yet urban residents' clean energy usage frequency remains low. Xining should strengthen residents' awareness of renewable energy and increase clean energy supply through rooftop photovoltaics and expanded natural gas pipeline networks.

Second, implement differentiated energy conservation publicity for different income groups. Middle- and high-income households should be targeted with policies promoting high-efficiency appliances, while low-income households should receive education on basic energy-saving behaviors like turning off lights. High-income households can reduce heating consumption through self-heating systems.

Third, coordinate regional development and adopt tailored energy policies. Regional household energy consumption must consider local and neighboring conditions, avoiding blind restrictions or encouragement. Policy subsidies and other measures should be combined to implement differentiated policies across regions with varying economic development levels.

Different geographical scales present frontier challenges in energy geography research regarding regional household energy structures, spatiotemporal processes, driving mechanisms, and effects. As a key component of the Qinghai-Tibet Plateau, where over 60% of areas exceed 4000 m in elevation and temperatures are significantly lower than same-latitude regions, energy consumption exhibits typical characteristics. While the plateau is rich in clean energy resources like solar radiation, clean energy shortages persist in social livelihood sectors, particularly in populated plateau towns. How to resolve this contradiction? Future research should explore how plateau-specific lifestyles affect energy consumption and how to efficiently heat homes during the 182-day heating season while reducing consumption and emissions. Currently limited by survey time and sample size, this study cannot precisely depict associated effects and mechanisms, resulting in considerable knowledge gaps for decision-making. With the rapid growth of multi-source geospatial data in the big data era, future spatial big data may enable more efficient identification of regional household energy consumption patterns, saving survey time while improving accuracy.

6 Conclusions

This study yields four main conclusions: (1) In 2021, Xining's urban households consumed 461.56 kgce $\cdot$ a^{-1} per capita, with Huangyuan County highest at 631.12 kgce $\cdot$ a^{-1}, followed by main urban districts (466.56 kgce $\cdot$ a^{-1}) and Datong County (398.26 kgce $\cdot$ a^{-1}). (2) Heating dominates energy use at 307.52 kgce $\cdot$ a^{-1} per capita (66.62% of total), followed by cooking (74.56 kgce $\cdot$ a^{-1}, 16.15%), water heaters (68.83 kgce $\cdot$ a^{-1}, 14.91%), refrigerators (10.27 kgce $\cdot$ a^{-1}, 2.23%), televisions (5.85 kgce $\cdot$ a^{-1}, 1.27%), lighting (2.17 kgce $\cdot$ a^{-1}, 0.47%), and washing machines (0.44 kgce $\cdot$ a^{-1}, 0.10%). (3) Total year-end household income is the core factor affecting per capita energy consumption, with consumption decreasing as income rises, primarily due to technological innovation and energy-efficient equipment replacing traditional high-consumption devices. Additionally, the number of household laborers negatively correlates with per capita consumption. (4) High-income households have more diverse energy types and greater per capita consumption, but heating energy consumption decreases with rising income as these households prefer self-heating systems that reduce waste.

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Note: Figure translations are in progress. See original paper for figures.