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Water and related electrical energy use in urban households—Influence of individual attributes in Beijing, China

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ABSTRACT

Water and energy are intricately connected in households. The connections mainly appear in three types of residential behavior: bathing, cooking, and cleaning. This study investigated the features of water and related energy consumption in groups with different individual attributes and identified the key groups and types of behavior that correlate with water and energy conservation. A face-to-face interview method was applied to estimate residential water and energy consumption associated with three types of behavior. Regression analysis was applied to the results of 1017 questionnaires to explore the relationships between individual attributes and the amount of water used and associated energy consumption. Chi-square test and extended Mantel-Haenszel test were applied to confirm the relations between individual attributes and behavior. Annual per capita water use for the three types of behavior was 33.6 m^3 on average and annual per capita water related electricity consumption was estimated to be 545.7 kWh. The Pearson correlation coefficient was 0.8 with a confidence level of 99%, which indicated a strong correlation between water use and energy consumption. The results showed that 55% of household electricity consumption was coupled with water use in Beijing. Water use and related electricity consumption had a positive correlation with education but a negative correlation with age and family size. Young women under 30 years old with a bachelor degree or above who live alone often use the most water and electricity, 16% and 28% higher than the average. This paper provides a better understanding of urban household consumption and individual attributes.

1. Introduction

Increasing awareness of water shortage and the effects of excessive energy use has attracted considerable attention to water-energy interdependencies (Kenway et al., 2015). Most attention has focused on the supply side, such as inter-basin water transfer projects (Sedoff et al., 2014), water pumping (Mo et al., 2011) and industrial production (Boix et al., 2012), where the goal is to satisfy the customer demands by having adequate supply of water and energy. A large amount of highly-coupled water and energy consumption, however, happens in the demand side, a large but heterogeneous group of small users (Escriva-Bou et al., 2015). Households are one of the main contributors to both water use and energy consumption (Jiang et al., 2016). Residential water and energy demand will continue to grow rapidly due to urbanization. This highlights the importance of observing the water and energy consumption of various households.

Many types of research have been conducted to investigate household water or energy consumption (Ren et al., 2016). Most of them can be classified into three categories. The first category is quantifying the household water or energy consumption. Such research often achieves the goal by modeling household expenditure (Cayla et al., 2011) or the consumption of different appliances (Willis et al., 2010) or types of behavior (Vieira et al., 2017). The usual conclusions will be the amount and structure of residential water used or energy consumed. For instance, research in the Netherlands found that water use for showering and using the washing machine accounted for 40% and 12% of total household water use, respectively (Shan et al., 2015). The second category analyzes the relations between water (or energy) consumption and individual attributes. Findings confirm that attributes including gender (Tong et al., 2017), age (Rathnayaka et al., 2017), education (Yu et al., 2011), and income (Yang et al., 2016) significantly affect household consumption. The linear regression method, the ordinal logit model, and other statistical methods are often used in these studies (Zhang and Brown, 2005). For example, some papers reported

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that larger households use more electricity overall, but have lower per capita electricity consumption (Poruschi and Ambrey, 2016). It has been found that households where the head is over 65 years old tend to use less electricity than those where the head is between 36 and 50 years old (Craig et al., 2014). The last category of research involves analyzing household behavior and individual attributes based on survey data. A descriptive statistical method has been widely used in these studies. A study from the United States (US) reported the frequency, duration and flow rate distribution of showering among people with different ages, gender, education, and income based on a national survey (Wilkes et al., 2005). Another paper analyzed water-related energy use by studying water end-use data from 504 households in China (Jiang et al., 2016).

Most of the studies mentioned so far focused on either household water or energy consumption. Few papers have incorporated both these two aspects (Binks et al., 2016). Kenway and Lam (2016) quantified the urban water related energy use based on three cases in Australia. Escriva-Bou et al. (2015) overcame lack of detailed data by analyzing the water related carbon footprints and costs in California using Monte Carlo simulations. Abdallah and Rosenberg (2014) developed a Monte Carlo-based approach to model household indoor water and energy use and their interactions from behavioral and technological perspectives. Unavailability of first-hand survey data prevented the detailed study of individual attributes that may influence consumption and behavior.

To the authors' knowledge, few researchers have fully discussed the interactions between water and energy from the demand side due to data limitation. It is necessary to deeply explore the interactions of household consumption, behavior, and individual attributes, in terms of both water and energy. The purpose of this study was to provide new evidence on the connections among attributes (i.e., gender, age, education and family size), behavior, and water and energy consumption using first-hand survey data and various statistical test approaches. Methods used in this study can be applied in other urban areas in the world, sometimes with minor adjustments of the categories chosen. This paper identified the amount and structure of household water and energy consumption. A comparison of water and energy consumption among groups with different attributes was used to identify features of consumption and key types of behavior for different groups. This study gives insight into the influence of individual attributes and behavior on household water and energy consumption. Such understanding will help us ensure that we do not simply transfer a burden to another resource dimension (e.g. energy use) when addressing one problem (e.g. water use). Results may prove useful for policy makers seeking specific ways for groups with different attributes, which simultaneously reduce water and energy use.

The paper is organized as follows: Section 2 outlines the research framework, methods and data sources. Quantitative results and related discussions are presented in Section 3 and Section 4. Some conclusions are outlined in the final section.

2. Methodology

A formal analytical framework is presented in Fig. 1. A face-to-face social survey was conducted to collect household attributes, behavior, and water and energy consumption data. The survey elicited detailed information on three types of residential behavior (i.e., bathing, cooking, and cleaning) since water and energy are often closely related in these cases (Kenway et al., 2016). Detailed information about the classification of behavior can be found in the supplementary materials. On this basis, household water use and related energy consumption can be calculated with technical parameters of different appliances. Statistical methods were used to analyze the relationships among attributes (i.e., age, gender, education and family size), behavior and water and related energy consumption. These were multiple regression, Chi-square test, and extended Mantel-Haenszel test. The details of the analytical methods are described in the following sections.

2.1. Household survey

The data used in this analysis were drawn from a household survey conducted between November 2016 and February 2017. The study area was the capital's new administrative sub-center in Tongzhou District, Beijing, China. The administrative sub-center has been under construction since 2015. It has an area of 155 km^2 in total. Detailed information about the new administrative sub-center can be found in the supplementary materials.

2.1.1. Questionnaire design

The questionnaire mainly contained three parts. The first section comprised water use behavior, including showering, foot bathing, cooking, house cleaning, and clothes washing. The questionnaire covered frequency, duration and method (e.g. whether they use hot or cold water, whether they use a dishwasher or wash by hand). A total of fifty-four types of behavior were covered in the questionnaire. The second part included questions about individual and family attributes, such as age, gender, family size, education, income, occupation and housing area. The last part asked about households' annual water, gas and electricity bills.

2.1.2. Sampling and survey method

The sampling method is of great importance in surveys, as it influences the representativeness of survey results. Random sampling can often ensure internal validity (Krishnaiah, 1988). Due to the cost and limitations of each sampling method, large-scale sample surveys are always undertaken with stratified multistage random sampling to improve survey accuracy (Altmann, 1974; Hunn, 2009).

The sampling methodology in this study was a combination of three-stage random sampling with stratification and Probability Proportionate to Size (PPS) sampling. The three-stage stratified

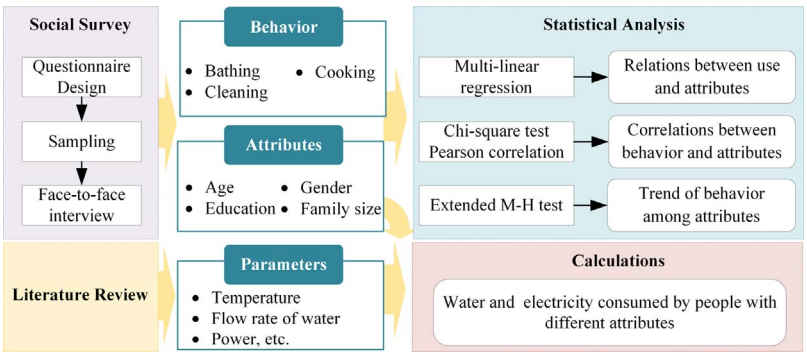

Fig. 1. A methodological framework to analyze household water and related electricity consumption based on survey data.