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Analysis on the evolution of residential water-energy nexus, a case study in Beijing China

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ABSTRACT

Economic development and the improvement in living standards have increased residential demand for water and energy. This research uses data of different water and energy consumption from 1978 to 2020, for analyzing the evolution of residential water and energy systems in Beijing. The results show that residential water consumption increased 140%, which from 58 L/(person day) to 139 L/(person day), energy consumption increased 540%, which from 0.06 KWh/(person day) to 3.30 KWh/(person day). It was found that mopping, dishwashing, laundry, and toilet flushing have changed from manual to automatic methods, even some households have changed to intelligent methods in Beijing households, following by the consumption of water and energy end-use. Although there is a high percentage of households who have used automated ways for water heating and drinking, still 5% use manual ways. As people gradually shift from manual ways to automated or intelligent ways, water and energy consumption have also changed dramatically. By calculating and comparing the utilization of water and energy in different ways, the systemic evolutionary trends were summarized, which including energy saving, the correlated growth of water and energy, and substitution of energy for water. Also the paper provides a theoretical contribution to the management of residential water and energy consumption.

Keywords: Residential, Water and energy consumption, Evolution, Beijing

1. INTRODUCTION

Water and energy are the critical resources for meeting basic human needs. The demand for residential water and energy in cities of China are increasing rapidly due to climate change and urbanization. According to statistics [1], China's urban residential water consumption was 28.393 billion m^3, and residential energy consumption was 167 million tons of standard coal (tce) in 2000. In 2020, those figures have increased to 62.95 billion m^3 and 617 million tce, an 120% and 270% increase, respectively. For all this, it was predicted that residential water and energy consumption will continue to rise in China [2]. Improving the efficiency of residential water and energy consumption, and reasonably regulating its excessive urban expansion are important tasks for urban management.

To date, there have been many research about the relationship between household water and energy, which focusing on the calculation of water and energy consumption, and the analyzing of water and energy saving. According to Wang et al. [3], laundry and showering accounts for about 55% of household water consumption, these two behaviors have the greatest impact on water consumption, saving water in these can save both energies at the same time. Vieira et al. [4] studied the relationship between household water and energy and the best plan of management, which taking a low-income family in the coastal city of Florianópolis in southern Brazil as an example. They found that by using water-saving devices and wastewater recycling at the same time, the home energy saving rate reached 48%. Escriva–Bou et al. [5] used the water-energy-carbon dioxide emission model of household end-use to optimize household water consumption and water-related energy fees and costs. The results show that reducing the use of high-energy-consuming appliances can reduce overall household water consumption by 24%. Energy consumption and carbon dioxide emissions related to water usage are reduced by 30% and 53% respectively. According to Salvo et al. [6], per capita

water consumption has decreased in 1 in 10 households, while electricity consumption has increased. This difference is mainly caused by low-income households lacking air conditioners that use water for heat dissipation.

However, few researchers pay attention to the evolutional characteristics of residential water and energy systems, or the change of water and energy consumption patterns. Economic and social development has shifted from rapid growth to high-standard development in China. Faced with rising demand for water and energy in households, water and energy saving from the end-use will help society establish a green consumption model. This is fundamental to ensuring the safety of urban resources and maintaining sustainable economic and social development. Analyzing the characteristics of residential water and energy consumption over a long period conduces to understand its historical evolution process and the reasons for the demand growth, and provide a theoretical basis for the research on household water and energy saving.

2. MATERIAL AND METHODS

2.1 Data resources

There are three categories of research data sources: (1) The residential water and energy consumption, utilization rate of household water and energy equipment are from the Beijing Statistical Yearbook (1978–2020) [1]. (2) The data on the structure of residential water and energy usage is derived from relevant literature on the analysis of residential water and energy usage in Beijing [7]. (3) The behavior and habits of Beijing residential water and energy consumption are derived from relevant literature [7], as well as the survey of Beijing residents collected by this research group.

2.2 Methods

It can be inquired from the Beijing Statistical Yearbook, that the total amount of residential water and energy consumption. According to the survey about domestic water and energy structure, the consumption value of each water and energy end-use can be calculated. The equations are as follows:

$$Q_{(i,n)}=Q_n*PQ_{(i,n)} \quad (1)$$

$$E_{(i,n)}=E_n*PE_{(i,n)} \quad (2)$$

Where, Q_n and E_n represent the residential water and energy consumption in the n year, respectively. $Q_{i,n}$(i= 1-6) indicates water consumption for shower, toilet, clothes washer, dishwasher, faucet and sink, respectively. The unit is L/(person day). $E_{i,n}$(i=1-4) indicates the energy consumption for clothes washer, water heater, smart devices (including dishwasher, mopping robot, vacuum cleaner and smart toilet), and other electrical appliances (TV, air conditioner, refrigerator, electronic products, and cooking appliances, etc.). The unit is KWh/(person day). $PQ_{i,n}$ and $PE_{i,n}$ represent the proportion of water and energy consumption, respectively.

When analyzing the evolution of residential water and energy consumption, utility pattern is divided into three different ways, including manual, automatic and intelligent ways. The utilization degree of residential water and energy use in different ways is calculated according to the equipment usage rate.

$$W_i=U_{(i,m)}/100+U_{(i,a)}/100+U_{(i,in)}/100 \quad (3)$$

Where, W_i indicates the proportion of manual, automatic and intelligent water utilization ways. $0<W_i\leqslant 1$ indicates a manual way, $1<W_i\leqslant 2$ indicates an automatic way, and $2<W_i\leqslant 3$ indicates an intelligent way. The larger the value of Wi, the higher the utilization. $U_{i,m}$, $U_{i,a}$, and $U_{i,in}$ indicate the proportion of manual, automatic and intelligent equipment or ways, respectively.

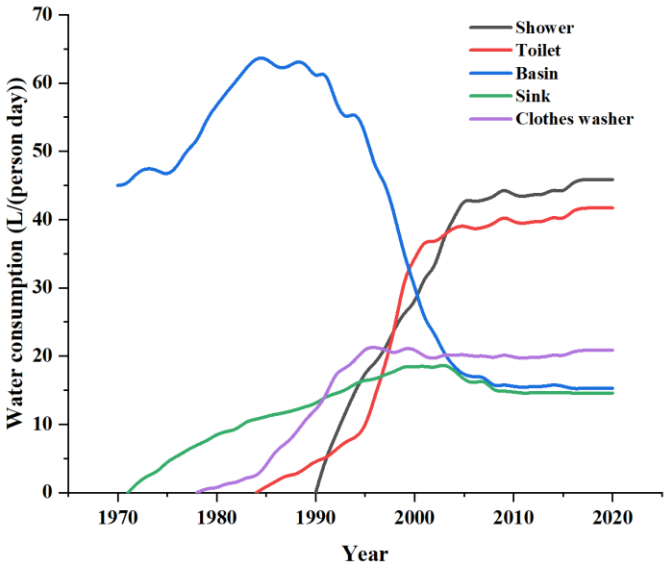
3. RESULTS

3.1 Evolution of residential water and energy consumption in Beijing

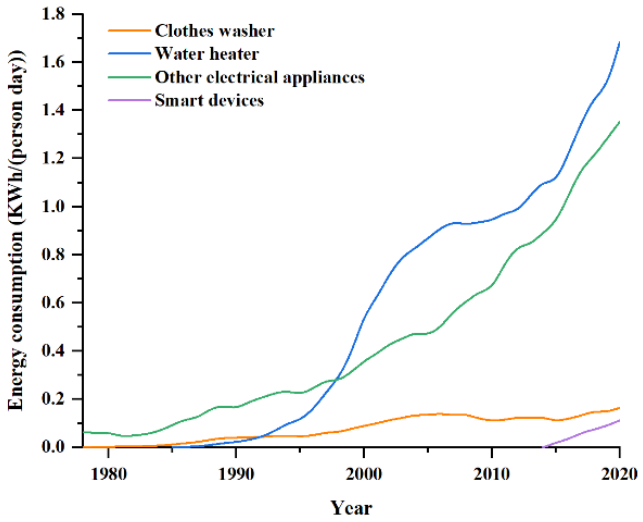
Due to the low penetration rate of other water facilities, the main water consumption end-use in Beijing households before 1990 were faucets and clothes washer, which accounted for 95% and 5% of water consumption, respectively (Fig. 1a). With the increasing penetration and upgrade of residential water facilities, residents' access to water has become more convenient after 1990, that leading to changes in the behavior of residential water consumption. At the same time, the structure of residential water usage shows some significant changes, end-use in household were tap (including faucet and sink), clothes washer, shower, and toilet. As the penetration rate of various types of water consumption end-use in Beijing households reached a relatively high level after 2005, residential water consumption and water systems have gradually become stable. Residential water consumption for tap, clothes washer, shower, and toilet was 31 L/(person day), 21 L/(person day), 46 L/(person day), and 42 L/(person day), respectively, in 2020. The percentages were 22%, 15%, 33%, and 30%, respectively.

Residential water and energy consumption increase simultaneously, with dramatic changes in the household energy structure (Fig. 1b). Electrical appliances in Beijing households were mainly clothes washer, TV, and

refrigerator before 1990. Less than 20% of the households had water heater. People used clothes washer relatively less due to the limitation of device functions and living habits. Water heater and clothes washer consume only 10% of total household energy. As the popularity of water heater and clothes washer in Beijing households increased rapidly from 1990 to 2000, their energy consumption increased to 0.55 KWh/(person day) and 0.09 KWh/(person day), respectively. Water heater became the electrical appliance in the household that consumed the most energy, which about 55%. Additionally, with the increased use rate of air conditioner in households, it's energy consumption has increased from 0.2 KWh/(person day) to 0.4 KWh/(person day). After 2000, although energy consumption was still increasing, residential energy consumption structure tends to be stable due to the high penetration rate. Smart devices became more popular in households after 2015, which resulting in another increase in energy consumption. In 2020, the energy consumption of clothes washer, water heater, and smart devices was 6%, 53% and 3.5%, respectively.



(a) Residential water consumption



(b) Residential energy consumption

Fig. 1 Evolution of residential water and energy consumption in Beijing

3.2 Evolution of water and energy utility patterns

Due to the change of behaviors and utilization ways, the manual utility pattern of water and energy was replaced by automatic and intelligent water utilization ways (Fig. 2). As the penetration rate clothes washer and toilet in Beijing households reached 100%, the ways of residents for laundry and toilet flushing changed from manual to automatic. Furthermore, the utility pattern changed into intelligent way, while clothes washer and dryer or smart toilet was used. Similarly, it started an intelligent way when mopping robot, vacuum cleaner and dishwasher were used in households, which replaced washing dishes and mopping floors manually. To meet the needs of showering or drinking, the way for consuming water and energy has changed from manual to automatic when heater or water dispenser were used water rather than heating cold water with gas boilers.

Presently, 100% of the water used in Beijing households have been automatic way for washing clothes, heating water, and flushing toilets, even some households started intelligent way. In the future, the proportion of intelligent ways that consume water and energy for various purposes will continue to increase, with the increase in the utilization rate of intelligent equipment, such as smart toilet, mopping robot, and all-in-one clothes washer and dryer.

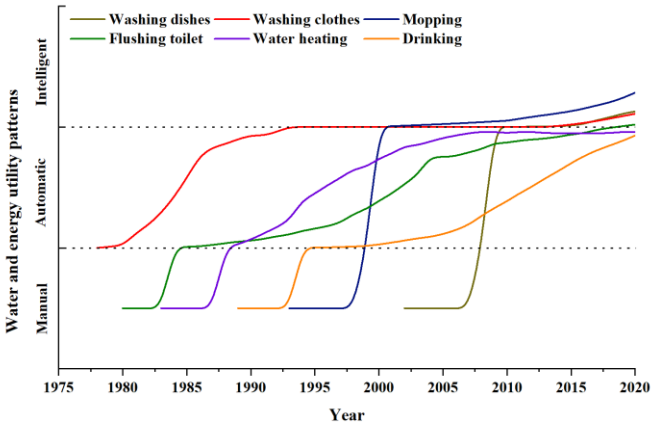


Fig. 2 Evolution of water and energy utility patterns in Beijing households

3.3 Differences in water and energy consumption among utility patterns

There are large differences in the consumption of water and energy among the different water utilization ways. Compared to using a clothes washer for laundry, hand-washing saves both water and energy. Due to the difference in appliance performance, the water and energy consumption of the pulsator clothes washer is 8–18 L/kg and 0.015 kWh/kg respectively, which are about 2 times and 0.1 times more than that of the drum type clothes washer. The energy consumption of a pulsator and drum clothes washer and dryer increased tenfold and twofold, respectively.

For the drinking water, the water purifier is the most water and energy efficient end-use for producing drinking water, which needing only 0.0005 kW h/L. The heating efficiency of the electric kettle is higher than the gas heating kettle, which required 0.11 kW h/L and 0.165 KW h/L, respectively. Moreover, although bottled water was not consumed energy directly for households, the process of its production, transportation, sales resulted in more resource footprint.

For the washing dishes, although the energy consumption of using a dishwasher is higher than hand-washing, the water consumption was only 50% of hand-washing. Comparing dishwashers of different capacities, it was found that it uses more water and energy compared to hand-washing with less than six sets of tableware.

For the household cleaning, manually mopping consumed about 0.04–0.13 L/m^2. Since mopping required cool water only, it not consumed energy. When using a mopping robot or a vacuum cleaner, water consumption was 0.013–0.016 L/m^2 and 0.01–0.03 L/m^2, respectively, which saved an average 80% of water compared to manual mopping. However, using intelligent cleaning tools consumed more energy, energy consumption was 0.0022 KWh/m^2 and 0.0013 KWh/m^2, respectively.

4. DISCUSSION

Residential water consumption in Beijing increased from 58 L/(person day) to 139 L/(person day) from 1978 to 2020, a 140% increase. Energy consumption increased from 0.06 KWh/(person day) to 3.30 KWh/(person day), a 540% increase. The increase in residential water and energy consumption can mainly be attributed to the improvement in residential water facilities and living standards. As there were no private toilet and bathroom in family, the acts of flushing the toilet and showering require public facilities were outside their residence. All the water consumption inside the family were from taps, the demand for water came from behaviors such as maintaining personal hygiene, laundry, cooking, and cleaning the household. The only water and energy consuming appliance inside family was clothes washer, which was used once or twice a week, it accounted for only 10%–20% of all energy consumption. In that time, the correlation between water and energy consumption was low, and most of patterns that use water and energy were in manual ways.

With economic development and the improvement of residents' living standards, Private toilet and bathroom were gradually popularized in households, which leading to the increasing of water and energy consumption for bathing and flushing the toilet. At the same time, the proportion of energy related to water consumption, such as clothes washer, water heaters and smart devices, exceeded 70% of the total household energy consumption, the automatic or intelligent ways were gradually replacing manual ways. As a result, water and energy consumption were becoming more closely related.

For laundry, the demand of water and energy in both automatic and intelligent ways has increased compared with manual way, and the evolution of water and energy consumption can be seen as the correlated growth of water and energy. The water consumption in automatic way has not changed significantly compared with manual way to producing drinking water, but it calculated that automatic way could save energy consumption by 33% to 95%. The evolution of water and energy consumption belongs to the energy saving category. Intelligent way used less water and more energy than manual way for dishwashing and mopping, the evolution is the substitution of energy for water.

5. CONCLUSION

This study analyzed the evolution of residential water and energy ways of Beijing residents from the

historical water and energy consumption at different end-use. Residents' daily lives through the required usage of water and energy at end-use such as laundry, dishwashing, toilet flushing, drinking, mopping, and water heating were calculated, for analyzing the evolution and utility patterns of manual, automatic and intelligent ways. As the results shown, the utility patterns of water and energy consuming undergone a significant change as residents gradually change from manual to automatic or intelligent ways. Furthermore, the evolution of water and energy related to different behaviors were summarized, by calculating and comparing the water and energy consumption in different utility patterns.

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