Investigating urban household water - energy nexus towards supporting sustainable and smart city policies: The case of Hanoi City, Vietnam

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Abstract. Sustainable and smart management of urban water and energy sectors is one of challenges facing by Vietnamese cities today. This study examined the water-energy nexus in urban households by analysing the “cause-and-effect” relationships among four major individual attributes (age, gender, education level, and family size) and three household behaviours (showering, cooking, and washing) with water and water related energy uses for the case of Hanoi City. The amount and component of water and water related energy uses with respect to those household behaviours and individual attributes were explored. The results showed that both water use and water related energy use had relationship with gender, education level, and family size. Specifically, people with more water and energy uses were female with age ≤ 30 years old, especially who have higher education level and live alone. The better understanding on how household behaviours and individual attributes influencing the household water and water related energy uses provided by this study could help the urban planners, policy makers, and relevant stakeholders to identify the opportunities for designing better and smart solutions for household water and energy management, towards achieving the goals of sustainable and smart cities.

1. Introduction

Cities are considered as a complex ecosystem comprising a number of sectors including mobility, building, energy, water and waste management, and public services [1]. As urban areas are expanding rapidly, the transformation of existing cities into smart cities as well as the development of new smart cities require the sustainable and smart management of these sectors. A smart city is an efficient and sustainable urban centre that would provide its citizens with a high quality of life by optimising the urban resources [2]. As water and energy are two of the most important sectors in all cities, on-going works on urban transformation towards smart cities should explore a variety of technological and management innovations while taking into account the availability of urban resources and the demand of different stakeholders to minimise trade-offs and maximise synergies at the linkage between urban water and energy.

Recently, the Government of Vietnam has put considerable efforts to speed up the progress of transformation of existing cities into smart cities with the Master Plan for Vietnam’s Smart and Sustainable City Development Strategy in the 2018-2025 period, with a vision towards 2030. However, due to the rapid urbanisation and increasing urban population, Vietnamese cities are facing a number of complex interrelated challenges across sectors. The rapid urbanisation is now placing a huge pressure on the increasing demand for water and energy among the sectors. In order to assure the
efficient management of these two sectors, the urban water-energy nexus should be fully understood. There is a critical need to determine energy used for water consumption, supply and distribution for both public or private sector. Within cities, households call for specific attention as they are a major building block in cities. For better understanding on the urban water-energy nexus, it is important to understand that nexus at the household scale. However, the linkage between water and energy in households has acquired less attention than those for utilities and the water-energy nexus in households is poorly defined. While the impacts of technological factors (i.e. design and efficiency aspects of electric water heaters, solar water heater, hot water system) on household water-related energy use have been studied [3, 4, 5, 6, 7, 8], however, few studies on assessing the impacts of household behavioural factors and individual attributes on water-energy nexus across different water end uses in households have been done so far. On the other hand, most of previous studies have concentrated on either water or energy use in households without the simultaneous consideration for the interactions of both these two aspects. It is important to fully investigate the interconnections among household uses, behaviours, and individual attributes for water and energy, in order to provide more insights on the household water-energy nexus. For addressing these knowledge gaps, this study aims to evaluate the relationships among four major individual attributes (age, gender, education level, and family size) and three household behaviours (showering, cooking, and washing) with water and water related energy uses based on the primary survey data and statistical analysis. The nexus of water-energy representing the interconnection between water and energy in households will be analysed. The amount and component of water use and water related energy use in households will be investigated. The compared analysis of water and water related energy uses among groups with different individual attributes will shed the light on the characteristics of water use and water related energy use as well as the key types of behaviour for different groups in households that related to water and related energy uses. The better understanding on the impact of individual attributes and behaviours on water use and water related energy use in households will provide useful information for policy- and decision-makers in developing and implementing appropriate policies, strategies and plans for sustainable and smart management of both water and energy in households and improve the resource efficiency of cities, towards achieving the goals of sustainable and smart cities for Vietnamese cities.

2. Research methods
2.1. Household survey
A face-to-face survey using the questionnaire was carried out during the period from November 2018 to April 2019 to collect household data in the largest (in terms of area) district of Hanoi City – Long Bien district with the area of 60.38 km², total population of 291,900, and population density of 4,834 persons/km². The information on water use behaviours (showering, cooking, and washing) including the usage frequency, length of time, and way (i.e. using cold or hot water, washing clothes by hand or washing machine) and individual attributes including age (≤ 30, 31-40, 41-50, 51-60, and > 60), gender (male and female), education level (high school, undergraduate, and graduate), and family size (1, 2, 3, 4, and >4) was collected.

This study employed the three-stage random sampling with stratification together with probability proportionate to size (PPS) sampling. PPS sampling was applied for all of 14 wards belong to Long Bien district. Based on the proportion of population for each ward, the number of communities for each ward was acquired, and totally 33 communities were selected for studying. Within each ward, the communities were selected basing on systematic random sampling (SRS). Finally, 15 individuals from 15 different households in each studied community were selected using SRS method. In total, 495 valid questionnaires were acquired for this study.

2.2. Estimation of water and water related energy uses in households
2.2.1. Estimation of water and water related energy uses for showering activity
Annual water use per capita for showering activity is estimated as

\[ W_{sh} = \sum_{i=1}^{4} d_i f_{sh} t_{sh} F_{sh} \]  

(1)
where $W_{sh}$ was the annual water use per capita for showering ($m^3$); $i = 1, 2, 3, 4$ was the seasons corresponding to spring, summer, autumn, and winter; $d_i$ was the days of season $i$; $f_{sh_i}$ was the frequency of showering in season $i$ (times/day); $t_{sh_i}$ was the length of showering each time in season $i$ (seconds/time); and $F_{sh}$ was the flow rate of showering tap ($m^3/s$).

Annual energy use per capita for showering activity is estimated as

$$E_{sh} = \frac{\theta}{\eta} \sum_{i=1}^{4} c_w \rho_w f_{sh_i} F_{sh} (T_{heat} - T_{cool})$$

(2)

where $E_{sh}$ was the annual energy use per capita for showering (kWh); $\theta$, was the factor for unit conversion between joule and kWh; $\eta$ was the heating efficiency of water heater; $c_w$ was the heating capacity of water (joule/kg °C); $\rho_w$ was the density of water (kg/m$^3$); $T_{heat}$ and $T_{cool}$ were the temperature of hot and cool water, respectively.

2.2.2. Estimation of water and water related energy uses for cooking activity

In this study, water and energy uses for cooking activity were considered for three steps in cooking: food preparation (before cooking), cooking, and dish washing (after cooking and meal). Annual water use per capita for cooking activity is estimated as

$$W_{co} = 365 \left[ f_{co} (n_d n_{bfco} w_{bfco} + \sum_{m=1}^{3} i_{afcom} n_{afcom} t_{afcom} w_{afcom}) + \sum_{j=1}^{n} i_{incoj} f_{incoj} w_{incoj} \right]$$

(3)

where $W_{co}$ was the annual water use per capita for cooking ($m^3$); $f_{co}$ was the frequency of cooking (times/day); $n_d$ was the number of dishes for each meal; $n_{bfco}$ was the number of times that food was washed before cooking; $w_{bfco}$ was the water amount utilized for washing food per time ($m^3/time$); $m = 1, 2, 3$ were corresponding to the running water, basin, and dish washing machines; $i_{afcom} = 1$ and 0 if the $m$th dish washing way was used and not used, respectively; $n_{afcom}$, $t_{afcom}$ and $w_{afcom}$ were the times of washing, duration of washing and water amount used for each time of washing way $m$, respectively; $i_{incoj}$ indicated if the appliance $j$ was used or not used; $f_{incoj}$ and $w_{incoj}$ were the using frequency and water amount used for each time of the $j^{th}$ appliance, respectively.

Annual energy use per capita for cooking activity is estimated as

$$E_{bfco} = 365 \frac{\theta}{\eta} \alpha_{heco} c_w \rho_w f_{co} n_d n_{bfco} w_{bfco} (T_{heat} - T_{cool})$$

(4)

$$E_{inco} = \sum_{j=1}^{n} i_{incoj} f_{incoj} e_{incoj}$$

(5)

$$E_{afco} = 365 \frac{\theta}{\eta} \sum_{m=1}^{3} i_{afcom} n_{afcom} t_{afcom} w_{afcom} (T_{heat} - T_{cool})$$

(6)

$$E_{co} = E_{bfco} + E_{inco} + E_{afco}$$

(7)

where $E_{bfco}$, $E_{inco}$, and $E_{afco}$ were the energy use for food preparation, cooking, and dish washing, respectively (kWh); $E_{co}$ was the total energy use for cooking (kWh); $\alpha_{heco}$ was the percentage of hot water used for cooking; $e_{incoj}$ was the energy use for each time of the appliance $j$ (kWh/time).

2.2.3. Estimation of water and water related energy uses for washing activity

Annual water use per capita for clothes washing activity is estimated as

$$W_{wam} = \sum_{i=1}^{4} d_i (i_{wam} f_{wam} i_{Mwam} w_{wam} + i_{wah} f_{wah} N_{wah} w_{wah})$$

(8)

where $W_{wam}$ was the annual water use per capita for clothes washing ($m^3$); $f_{wam}$ was the using frequency for washing machine in season $i$ (times/day); $M_{wam}$ was the capacity of washing machine (kg); $N_{wah}$ was the times of rinsing for each washing; $i_{wam} = 1$ and 0 if clothes were washed by washing...

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machines and were not, respectively; \( i_{\text{wash}} = 1 \) and 0 if clothes were washed manually and were not, respectively; \( w_{\text{num}} \) and \( w_{\text{wash}} \) were the water amount used for washing machine and hand washing each time \( (\text{m}^3/\text{capacity/time and m}^3/\text{time}), \) respectively.

Annual energy use per capita for clothes washing activity is estimated as

\[
E_{\text{wash}} = \sum_{i=1}^{4} d_i [l_{\text{wash}} f_{\text{wash}} d_i M_{\text{wash}} e_{\text{wash}} + \frac{\theta_i}{n_i} \alpha_{\text{wash}} i_{\text{wash}} e_{\text{wash}} \rho_{\text{wash}} N_{\text{wash}} w_{\text{wash}} f_{\text{wash}} (T_{\text{heat}} - T_{\text{cool}})]
\]

where \( E_{\text{wash}} \) was the annual energy use per capita for clothes washing (kWh); \( e_{\text{wash}} \) was the energy use per capacity for washing machines each time \( (\text{kWh/capacity/time}); \) \( \alpha_{\text{wash}} \) was the percentage of hot water used for rinsing.

2.3. Data analysis

To investigate the effect of individual attributes on water use and water related energy use, this study employed the multivariate statistical analysis method [9] as the following.

\[
A = f(Y_1, Y_2, ..., Y_n) + u
\]

where \( A \) was the annual amount of water use or water related energy use per capita. \( Y_1, ..., Y_n \) were the explanatory independent variables, and \( u \) was the intercept term. For our study, four individual attributes of age, gender, education level, and family size were considered as the independent variables. The linear function and stepwise regression were employed in the analysis. The conversion of dependent variables to natural logarithm [10] was made for addressing the problems of potential heteroscedasticity. The functions expressing the relationships between water/energy uses and individual attributes were made as the following.

\[
\ln \text{water} = \alpha_{\text{water}} + \beta_{\text{water}, \text{age}} + \beta_{\text{water, gender}} + \beta_{\text{water, education level}} + \beta_{\text{water, family size}}
\]

\[
\ln \text{energy} = \alpha_{\text{energy}} + \beta_{\text{energy, age}} + \beta_{\text{energy, gender}} + \beta_{\text{energy, education level}} + \beta_{\text{energy, family size}}
\]

where the coefficients \( (\beta_{\text{water, age}}, ..., \beta_{\text{water, gender}}, \beta_{\text{energy, age}}, ..., \beta_{\text{energy, family size}}) \) indicated the percentage of change on the corresponding individual attributes in the relation to water use and water related energy use. In this study, SPSS software was used for the statistical analysis of the surveyed data. In data analysis, the statistical significance was set to 10%.

3. Results and discussions

3.1. Water and water related energy uses for showering activity

The annual water use and water related energy use per capita for showering activity by four individual attributes are shown in Figure 1. The annual water use and water related energy use per capita for showering were about 14.2 m\(^3\) and 361.8 kWh, respectively. The regression analysis (Table 1) showed that three individual attributes of age, gender, and education level significantly influenced the water use and water related energy use for showering.

It is seen that both water use and water related energy use for showering decreased with increased year of age. On average, the annual water use per capita for showering for people \( \leq 30 \) years old was 16.8 m\(^3\) which 30.3% more than that for people \( > 60 \) years old. There was a trend that water used for showering decreased with age.

In terms of gender, it was observed that females used 12.2% of water and energy for showering more than males did. Particularly, females used about 15 m\(^3\) of water for showering annually, while males used only 13.2 m\(^3\). Water related energy used by females was 392.5 kWh, which was also more than that for males.
Table 1. Regression results for behaviours and individual attributes with water and water related energy uses.

| Dependent variable | Independent variable | α      | Age     | Gender | Education | Family size |
|--------------------|----------------------|--------|---------|--------|-----------|-------------|
| Showering lnwater  |                      | 2.91   | -0.013  | 0.172  | 0.016     | 0.006       |
| Showering lnenergy |                      | 6.14   | -0.013  | 0.172  | 0.016     | 0.005       |
| Cooking lnwater    |                      | 1.812  | 0.015   | 0.031  | -0.026    | -0.123      |
| Cooking lnenergy   |                      | 4.124  | 0.018   | -0.012 | 0.014     | -0.242      |
| Washing lnwater    |                      | 2.436  | -0.010  | 0.093  | 0.015     | -0.186      |
| Washing lnenergy   |                      | 3.623  | -0.010  | 0.039  | 0.026     | -0.115      |
| Total lnwater      |                      | 3.725  | -0.001  | 0.124  | 0.008     | -0.091      |
| Total lnenergy     |                      | 6.492  | -0.005  | 0.115  | 0.017     | -0.052      |

Note: * For regression analysis, female and male were assigned to be 1 and 0, respectively; ** p < 0.05; *** p < 0.01

Figure 1. Annual water and water related energy uses per capita for showering activity by four individual attributes.

For increased education level, water use and water related energy use for showering both increased by 1.6%. The annual water use per capita for showering for people with high school level was 14.2 m³.
Meanwhile, people with undergraduate and graduate levels consumed more. Similarly, the annual water related energy use per capita for showering was 350 kWh for people with high school level which lower than those for people with undergraduate and graduate levels.

3.2. Water and water related energy uses for cooking activity

The annual water use and water related energy use per capita for cooking activity by four individual attributes are shown in Figure 2. The annual water use and water related energy use per capita for cooking were about 6.7 m³ and 89.8 kWh, respectively. According to the multi regression analysis (Table 1), age, education level, and family size had significant impact on water use for cooking while only age and family size influenced water related energy use for cooking.

![Figure 2. Annual water and water related energy uses per capita for cooking activity by four individual attributes.](image)

It is observed that both water use and water related energy use for cooking correlated positively with age and they are found to increase with age. Whereas, water use and water related energy use for cooking correlated negatively with family size. The annual water use per capita for cooking of people with age ≤ 30 years old was 5.3 m³ which 42% lower than that of people with age > 60 years old. Meanwhile, the annual water related energy use per capita for cooking of people with age > 60 years old was 114.5 kWh which 44.4% higher than that for young people ≤ 30 years old. Both water use and water related energy use for cooking were observed to increase with age since the older people
naturally prefer to cook at home. For example, the statistical analysis of survey data showed that the cooking frequency of young people with age ≤ 30 years old was only 1.3 times/day while the cooking frequency of old people with age > 60 years old was about 2.6 times/day.

It is found that water use for cooking decreased as education level increased. Particularly, water use for cooking dropped by 2.6% as education level additionally increased. The annual water use per capita for cooking of people with high school level was 7.4 m$^3$. Meanwhile, people with undergraduate and graduate levels consumed 16.3% and 22.5%, respectively less than people with high school level did. Whereas, water related energy use for cooking did not show the downward trend as water use for cooking did. The decreased trend of water use for cooking with education level could be attributed to the decreased trend in the frequency of cooking at home. As shown by the statistical data, the frequency of cooking decreased with the increased education level. Particularly, the frequency of cooking for people with high school level was 2.7 times/day, meanwhile those for people with undergraduate and graduate levels were 2.1 and 1.4 times/day, respectively.

With respect to the family size, with each additional family member, the annual water use and water related energy use per capita for cooking dropped by 12.3% and 24.2%, respectively. Particularly, the annual water use of households with only one person was 7.7 m$^3$ which 29.4% higher than that for households have more than four persons. The same trend was also seen for water related energy use in which households with only one person used 61.8% less than those for households with more than four persons. This implies that to some extent the efficiency of water and water related energy uses for cooking of large-size households was increased.

### 3.3. Water and water related energy uses for washing activity

The annual water use and water related energy use per capita for clothes washing activity by four individual attributes are shown in Figure 3. It was evaluated that the annual water use and water related energy use per capita for washing were 7.9 m$^3$ and 41 kWh, respectively. Table 1 showed that water use was significantly influenced by age, gender, education level, and family size. Meanwhile, water related energy use was influenced by three attributes including age, education level, and family size. There was a trend that both water use and water related energy use for washing decreased with increased year of age. The annual water use and water related energy use per capita for washing by people with age ≤ 30 years old were 9.2 m$^3$ and 45.8 kWh, respectively. In comparison, the annual water use and water related energy use per capita for washing by people with age > 60 years old were 15% and 21.8% lower than those by people with age ≤ 30 years old.

With respect to gender aspect, the annual water use per capita for washing by females was 7.4% higher than that by males. On the other hand, water related energy use for washing was not significantly affected by gender. It was reported that the annual water use and water related energy use per capita for washing by males were 7.3 m$^3$ and 37.5 kWh, respectively which correspondingly 7.4% and 8.2% lower than those by females. The survey results showed that the frequency of clothes washing for females was higher than that for males.

For education aspect, with every extra education level, the annual water use and water related energy use per capita for washing increased by 1.5% and 2.6%, respectively. The annual water use and water related energy use per capita for washing by people with high school level were 7.3 m$^3$ and 41.3 kWh, respectively which correspondingly 6.4% and 2.8% lower than those of undergraduate people, and 12% and 8.2% less than those of graduate people. The increases in water use and water related energy use with education level were largely influenced by the frequency of clothes washing. The survey data showed that the frequency of clothes washing of people with undergraduate and graduate levels were higher than that of people with high school level.

With respect to family size, with every extra member in family, the annual water use and water related energy use per capita for washing dropped by 18.6% and 11.5%, respectively. Specifically, the annual water use and water related energy use per capita for washing by households have more than four persons were 5.8 m$^3$ and 36.5 kWh, respectively which 36.4% and 20.4% lower than those for households have only one person. The decreased water use and water related energy use for washing with increased family size was due to effect of the frequency of clothes washing and family size.
According to the survey data analysis, there was an increase in clothes washing frequency as family size increased in any season.

![Bar chart showing water use and water related energy use per capita for washing activity by four individual attributes.]

**Figure 3.** Annual water and water related energy uses per capita for washing activity by four individual attributes.

### 3.4 Total water and water related energy uses

The total annual water use and water related energy use per capita for three behaviours (showering, cooking and washing) by four individual attributes are shown in Figure 4. The total annual water use and water related energy use per capita were 28.8 m$^3$ and 492.6 kWh, respectively. As seen in Table 1, both total water use and water related energy use have correlations with gender, education level, and family size. It was found that the total annual water use and water related energy use by females were 10.2% and 9.9% higher than those by males. This was influenced by the larger amount of water and water related energy uses for showering of female. The highly educated people tend to use larger amount of water and water related energy for showering and washing, but not for cooking. The slight increase of water and water related energy uses with education level was due to the joint impact of the large proportion of water and water related energy uses for showering and washing. Generally, both water and water related energy uses decreased as family size increased. The annual water use and water related energy use per capita for a one-person household were 17.7% and 16.8% higher than that for a household with more than four persons. This implies that the efficiency of water use and water related energy use in large households could be higher.
In overall, young female with age $\leq 30$ years old, especially who have higher education level and living alone appeared to be the people with largest consumption of water and water related energy with 31.2 m$^3$ and 534.5 kWh, respectively which 7.6% and 7.8% more compared to the average values. It was found that they used more water and water related energy for showering and washing activity, however, used less for cooking activity.

![Figure 4](image_url)

**Figure 4.** Annual total water and water related energy uses per capita by four individual attributes.

4. Conclusions
This study examined the water-energy nexus for households in Hanoi City by analysing the “cause-and-effect” relationships among four major individual attributes (age, gender, education level, and family size) and three household behaviours (showering, cooking, and washing) with water use and water related energy use. The amount and component of water and water related energy uses with respect to household behaviours and individual attributes were explored. The improved understanding on how household behaviours and individual attributes influencing the water use and water related energy use in household provided by this study could help the urban planners, policy makers, and relevant stakeholders to identify the opportunities for designing better and smart solutions for household water and energy management, towards achieving the goals of sustainable and smart cities.
Acknowledgments

This research is funded by National University of Civil Engineering (NUCE) under grant number 197-2018/KHXD-TD.

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